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ENERGY SUPPLY, DEMAND/NEED AND THE GAPS BETWEEN

VOLUME II. MONOGRAPH, WORKING PAPERS AND APPENDIX PAPERS

MASSACHUSETTS INSTITITE OF TECHNOLOGY

1 DECEMBER 1974

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ENERGY SUPPLY, DEMAND/NEED AND THE GAPS BETWEEN

VOLUME II: MONOGRAPH, WORKING PAPERS AND APPENDIX PAPERS

by

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VOLUME II: MONOGRAPHS, WORKING PAPERS, AND APPENDIX PAPERS

of

FINAL REPORT ON

Energy
Supply, Demand/Need
and the
Gaps Between

to

The M.W. Kellogg Co.
Houston, Texas

and

The Environmental Protection Agency

under

Task 27 of EPA Contract 8-02-1308

James W. Meyer
William J. Jones
Myer M. Kessler

December 1, 1974

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Appendix Paper No. 17 - Solar Energy

Richard H. Baker
December 1, 1974
Amended June, 1975
William J. Jones

Monograph No. 1
MIT Energy Laboratory
SOLAR ENERGY

PRECIS

New Hampshire has an average annual solar power flux of 135 watts/M^2 with a daily mean of 60 watts/M^2 in December and 240 watts/M^2 in July. Day to day variations between peak and average are 1.5 to 1 in the winter and 2 to 1 in the summer. The dispersed nature and variability of this energy are serious challenges to its ability to provide large amounts of reliable electric power service. Large collectors and sizeable storage are essential.

There are two methods for converting solar energy to electrical power. Photovoltaic Conversion produces power directly from silicon or Cd sulphide solar cells. Silicon panels currently cost \$40,000/M^2 or about \$300/watt. Total photovoltaic conversion equipment, to produce 60 cycle 120 volt ac in New Hampshire, would currently cost about \$1200/watt of capacity. Projections indicate that with today's technology this could be reduced to about \$10/watt in a few years and perhaps ultimately below \$1/watt.

Solar/Thermal/Electric conversion systems heat water or other two phase fluids such as ammonia or Freon to the gaseous state to drive turbine-generators. To achieve high temperatures for thermal efficiency, concentrators for the incident solar radiation are necessary. Estimates of concentrators in the southwestern United States range from \$60/M^2 to \$1800/M^2 (in volume production). In New Hampshire, assuming the same construction cost, this would mean a cost between \$4/watt and \$12/watt.

To produce 1000 MWe (average), allowing for steam turbine efficiency and concentrator losses, would require a concentrator area, allowing for other facilities, of about 33×10^6 M^2 (10,000 acres) oriented to the south and at 45° to the vertical and a land area of about 200×10^6 M^2 (about 50,000 acres or 9 miles x 9 miles). Unsolved technical problems include deterioration of collector reflective surfaces and increasing the collector output temperature. One limitation is that clear skies, to insure parallel rays, are necessary for a concentration. Present designs are projected to operate at an efficiency of about 50% at 500°C.

To solve the energy storage problem, latent heat storage, using rocks, salt, etc., of about 1000°C, has been proposed for short-term storage and the production of hydrogen fuel for long-term storage. Hydrogen production by high pressure electrolysis at an energy efficiency of 80% to 94% appears practical. A 1000 MWe plant would reduce about 6×10^5 kg of hydrogen from 1.5 million gallons of pure water per day. The hydrogen, stored unpressurized, would require about 7×10^4 M^3 of storage. The electrolysis/storage system is projected to cost $100/kg of hydrogen produced per day or 60 million dollars.

A cooling tower facility would be needed for the solar/thermal system because in New Hampshire a solar plant is too large (15 KM x 15 KM) (9.3 miles x 9.3 miles) to locate near a large body of water.

A dry cooling tower facility to handle 1000 MWe has not been designed. The cost of a wet cooling tower is projected at $60 M/MWe. The size of a natural draft hyperbolic wet tower would be approximately 125 meter (410 feet) (base) and 115M (375 feet) (height).

Solar augmented heating and cooling of individual buildings appears practical and desirable in New Hampshire.

Flat plate collectors can produce temperatures up to 50°C above ambient at an estimated cost of $\$45/M^2$ in volume production. Short-term thermal storage (≈ 1 day) using heated water or rocks is practical. An optimized system is about 200 gallons of water per square meter of collector area. Total space conditioning cost (installed) has been projected at about $\$2.00/10^6$ BTU of collected solar energy.

Systems for space conditioning using solar energy are compatible with electric heating and can be used to reduce peak demand while increasing the utilization of base load demand.

OUTLINE - SOLAR ENERGY

I. Parameters of Solar Energy
    A. Solar Conditions
    B. Solar Conversion
    C. Solar Applications

II. Solar Energy for Electric Power Generation in New Hampshire
    A. New Hampshire Solar Flux
    B. System to Produce 1000 MWe
        1. Solar-Voltaic
        2. Solar-Thermal
        3. Energy Storage
        4. Cooling Tower
    C. Solar Augmented Space Heating

III. Summary

MIT ENERGY LABORATORY WORKING PAPER

SOLAR ENERGY

I. PARAMETERS OF SOLAR ENERGY

A. Solar Conditions

Outside the earth's atmosphere the sun is a steady source of energy. The solar constant, or energy received, is equivalent to 430 BTU/FT^2 per hour, or 1360 watts per square meter. On the surface of the earth the solar intensity is diminished by atmospheric absorption, becomes unsteady depending upon climatic conditions, and varies greatly with seasonal changes and terrestrial location. Figure 1 shows the effect of latitude on energy flux on a horizontal surface in June and December, including both clear days and average days together with the annual average value.[1]

Figure 1 shows that compared to the 1360 watts/M^2 that is available outside the atmosphere, or the 100 watts/M^2 on the earth's surface which is available when the sun is directly overhead on a clear day, the average daily input on the ground is significantly less. Also the latitude of a locality is considerably less important in determining its solar-energy reception than is the local cloudiness. By tilting a receiving surface toward the equator to favor the winter sun, a large part of the seasonal variation in solar incidence can be eliminated. The effect of collector tilt at 45° latitude is indicated in Figure 2.

B. Solar Conversion

The sun represents an enormous inexhaustible source of energy which can be harnessed. However, as shown by Figure 1 and Figure 2, the solar energy at the surface of the earth is highly variable and extremely dilute; its average flux density is only about five-hundreths of that of a modern steam boiler. In most applications, solar energy must be concentrated, converted to a more useful form, and then stored for use when the sun is not available. The fuel (solar energy) is free, but the equipment associated with concentration, conversion, and storage can be expensive.

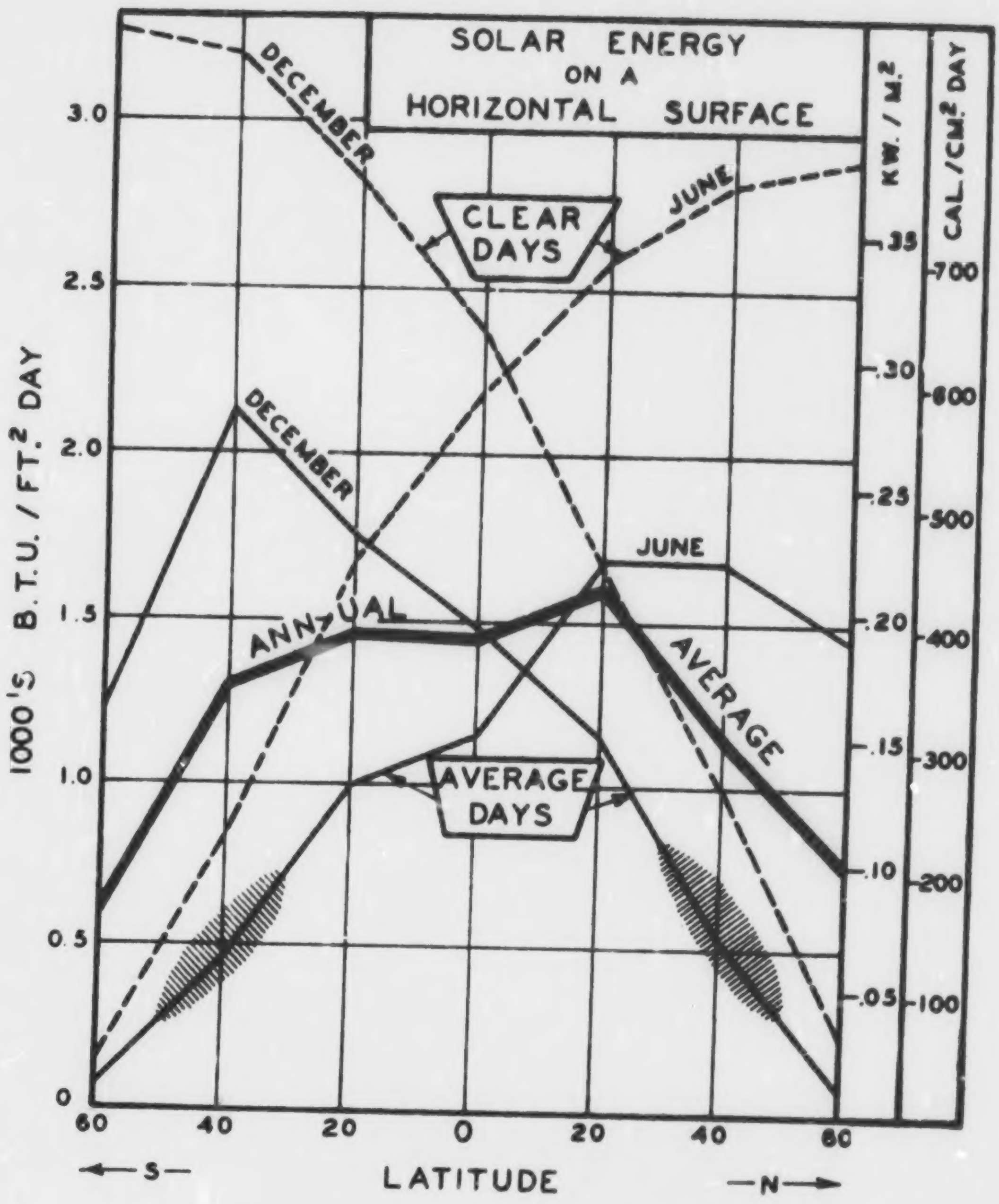


Figure 1: Solar-Flux Latitude

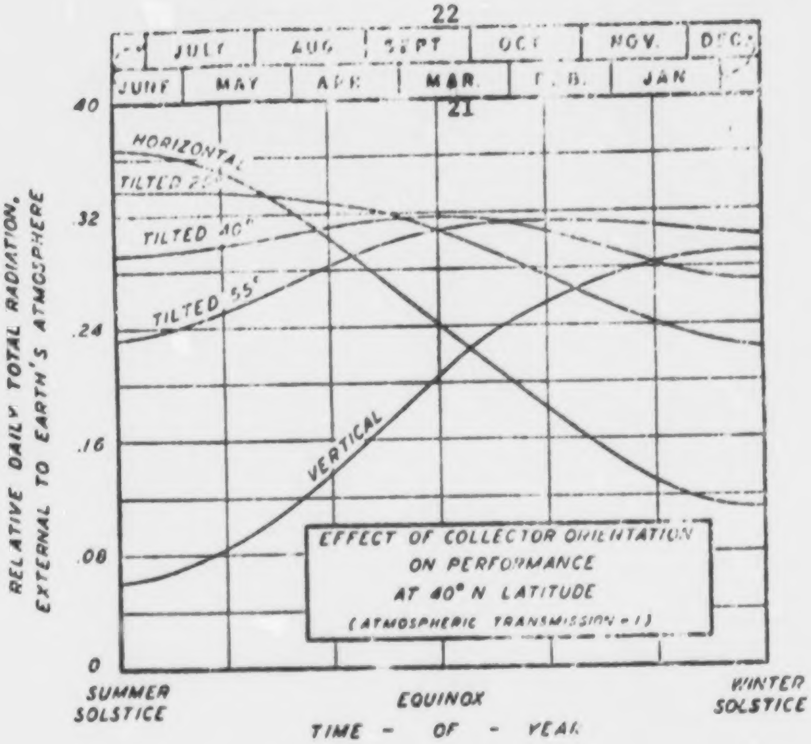


Figure 2: Effect of Collector Tilt

Reference 1

There are a variety of energy-conversion techniques;[2] solar radiation may be converted to electricity by solar cells and may be utilized in conventional heat engines (such as steam turbines). Electricity can also be generated indirectly from the sun in the form of winds or ocean thermal gradients.[3,4] Gaseous, liquid, and solid fuels can also be produced by direct solar radiation in a number of ways; photodecomposition of water, photosynthetic growth of organic matter which can be converted to fuels by destructive distillation, fermentation, by high pressure chemical processing, or photochemical conversion processes. These renewable fuels can in turn be used in conventional energy processing plants to produce electrical energy. The type of solar energy appropriate to fulfill a need is dependent upon a complex set of socio-economic conditions, but certain invariant parameters are discernable:

(1) The sun is a uniformly distributed source.

(2) Although solar flux is higher in equatorial zone (± 23°), it is sufficient, up to perhaps ± 45° latitude, to satisfy most applications providing sufficient storage can be implemented to compensate for varying climate conditions.

(3) The solar flux is so dilute that to produce temperatures in a working fluid greater than about 85°C above ambient requires concentration of the solar flux.

(4) Equipment for the collection of solar energy profits little by economics of scale.

(5) The day/night dependence and weather dependent variability of solar energy makes it necessary to include an energy storage facility in any (every) solar power system.

C. Solar Applications

There are three general ways that solar energy can be applied to augment conventional power systems:

Electric Power Generation - Directly from the sun using thermal and/or photovoltaic conversion techniques, or indirectly using wind or ocean thermal gradients.

Production of Synthetic Fuels - By photosynthesis of organic materials or electrolysis of water to produce hydrogen.

Production of Thermal Energy for Space Heating

II. SOLAR ENERGY FOR ELECTRIC POWER GENERATION IN NEW HAMPSHIRE

A. New Hampshire Solar Input

The average solar flux falling on a horizonal surface in various locations in the U.S. are shown in Figure 3.[6] The average solar flux can be used only when long-term storage is available (≈ 6 months). For systems with short-term storage (≈ 2 weeks), the winter values shown in Figure 4 must be used. Higher densities can be obtained by orientation of the solar collectors. Table I shows estimates of the annual and winter average flux intensities that would be available on oriented collectors in New Hampshire.

TABLE I

Collector Orientation	Estimate of Average Solar Energy Flux Density (Watts per Sq. Meter)* BTU/M^2 -hr Annual Average		December Average	
Fixed-Horizontal	(145)	500	(55)	185
Fixed-Facing South at 45° Above Horizontal	(160)	545	(130)	450
One-Axis Steerable in Elevation	(195)	665	(140)	475
Two-Axis Steerable	(270)	925	(145)	500

* Watts/M^2 x 3.41 = BTU/M^2 -hr

B. System to Produce 1000 MWe

Several studies have produced conceptual drawings that depict the large sclae use of solar cells (Figure 5 and Figure 6) or solar thermal concentrators (Figure 7) to generate electrical energy from the sun. A particularly imaginative proposal is one that generates power in space,

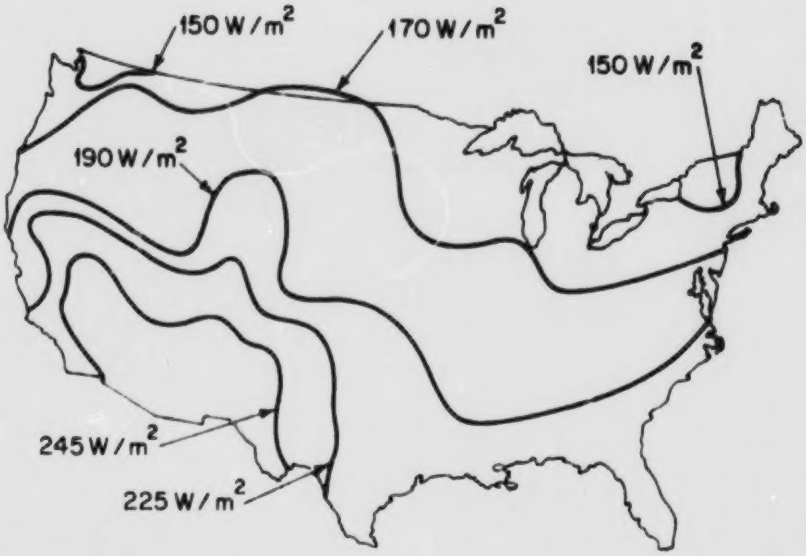

150 W/m^2
170 W/m^2
150 W/m^2
190 W/m^2
245 W/m^2
225 W/m^2

Fig. 3: Yearly Average of Solar Energy Incidence in Watts per Square Meter (Horizontal surface)

Reference 6

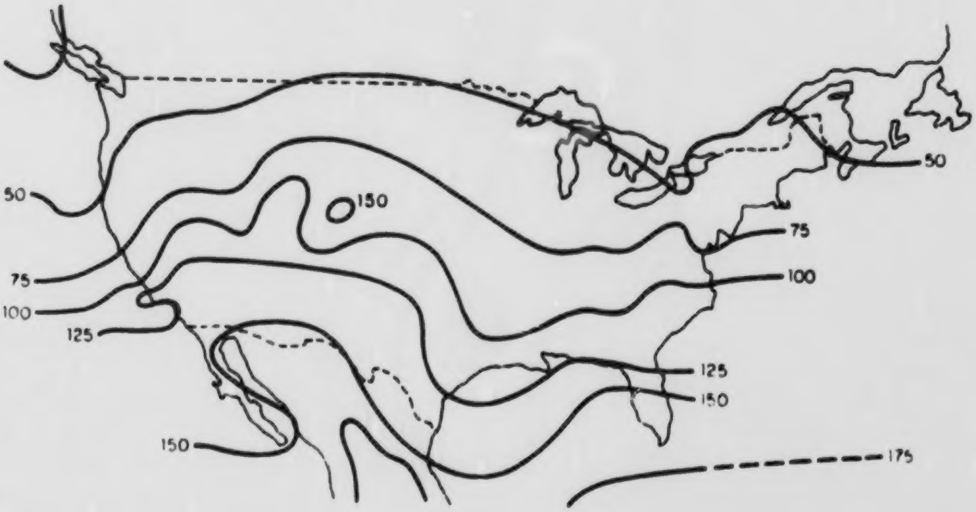

50
150
50
75
75
100
100
125
125
150
150
175

Fig. 4: December Average of Solar Energy Incidence in Watts per Square Meter (Horizonal surface)

Reference 6

SOLAR CELL PARK

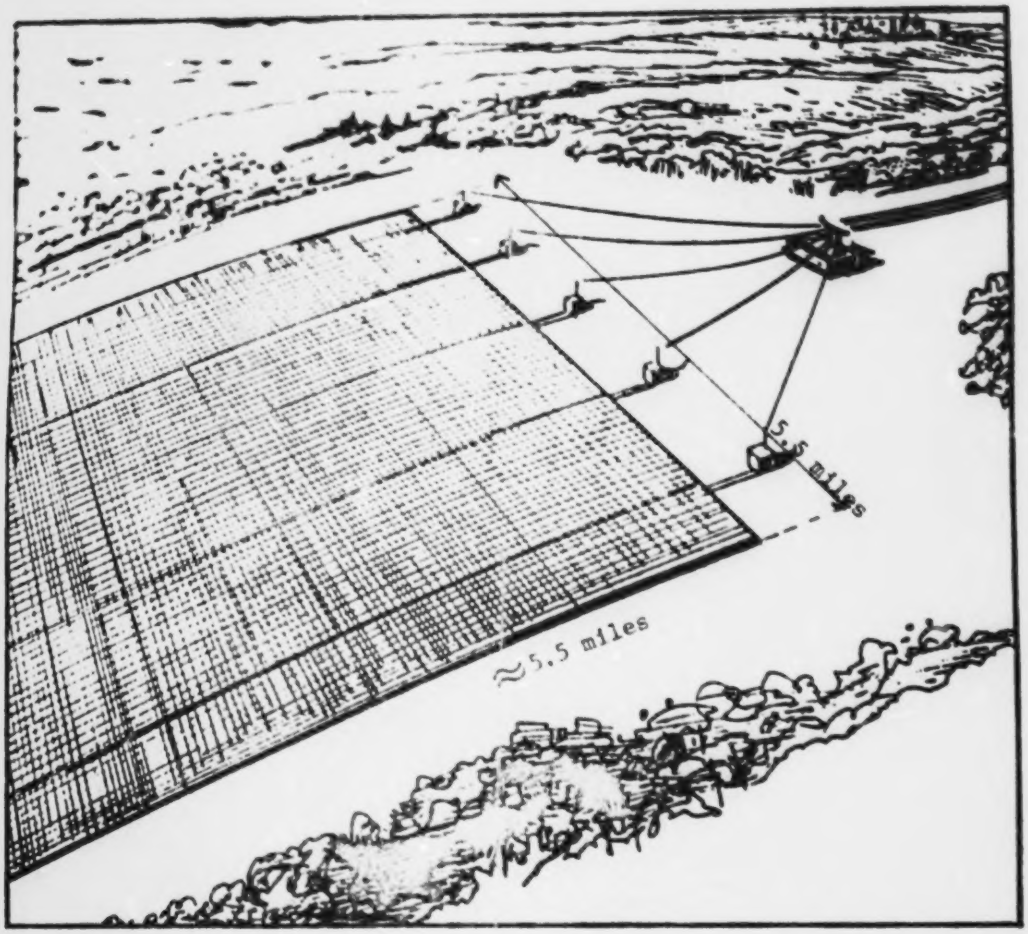

5.5 miles
≈5.5 miles

Figure 5: Power Generation with Solar Cells
1000 mWe

(Reference 14)

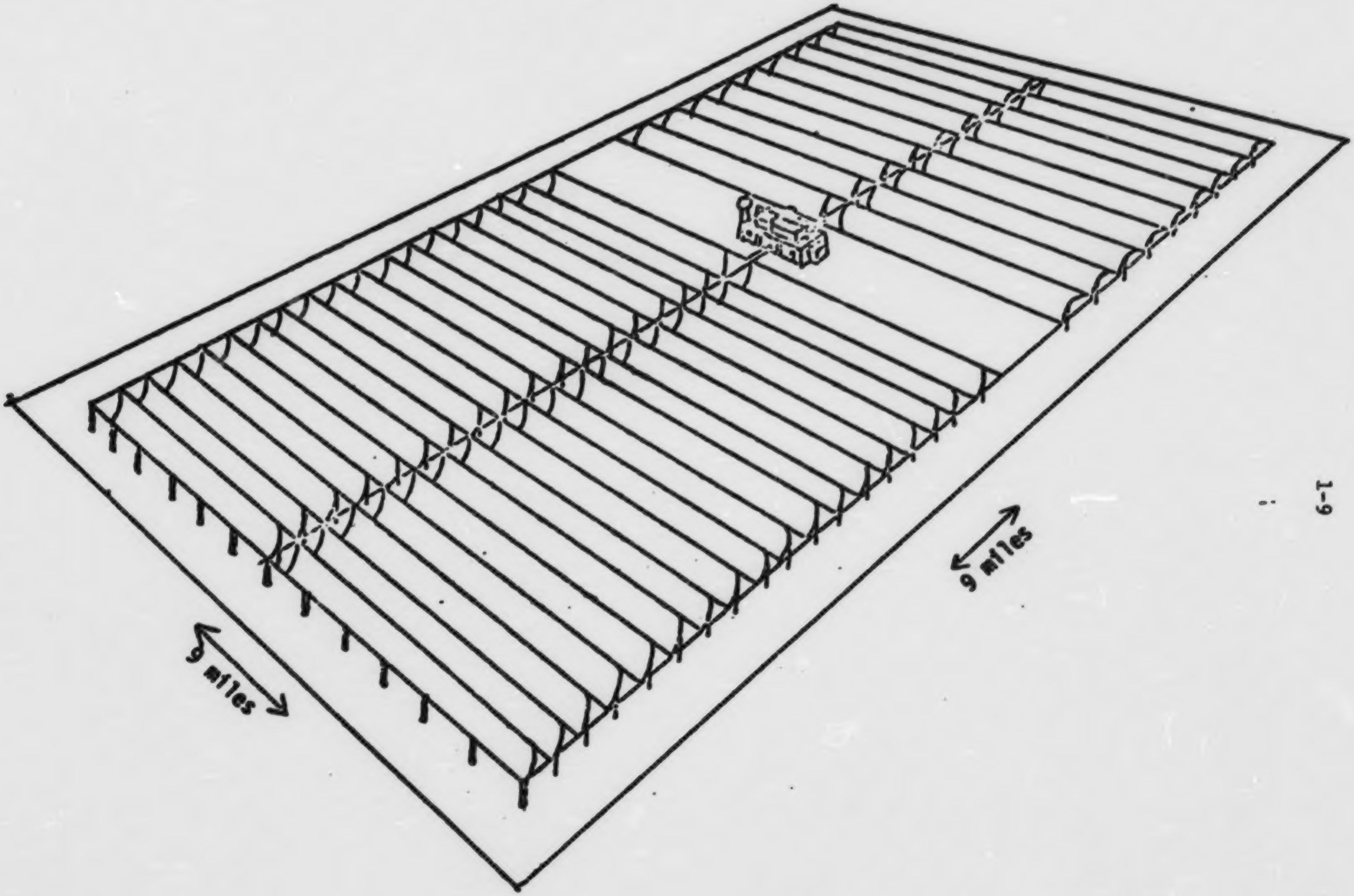

9 miles
9 miles

Figure 6: Solar Farm A

(Reference 14)

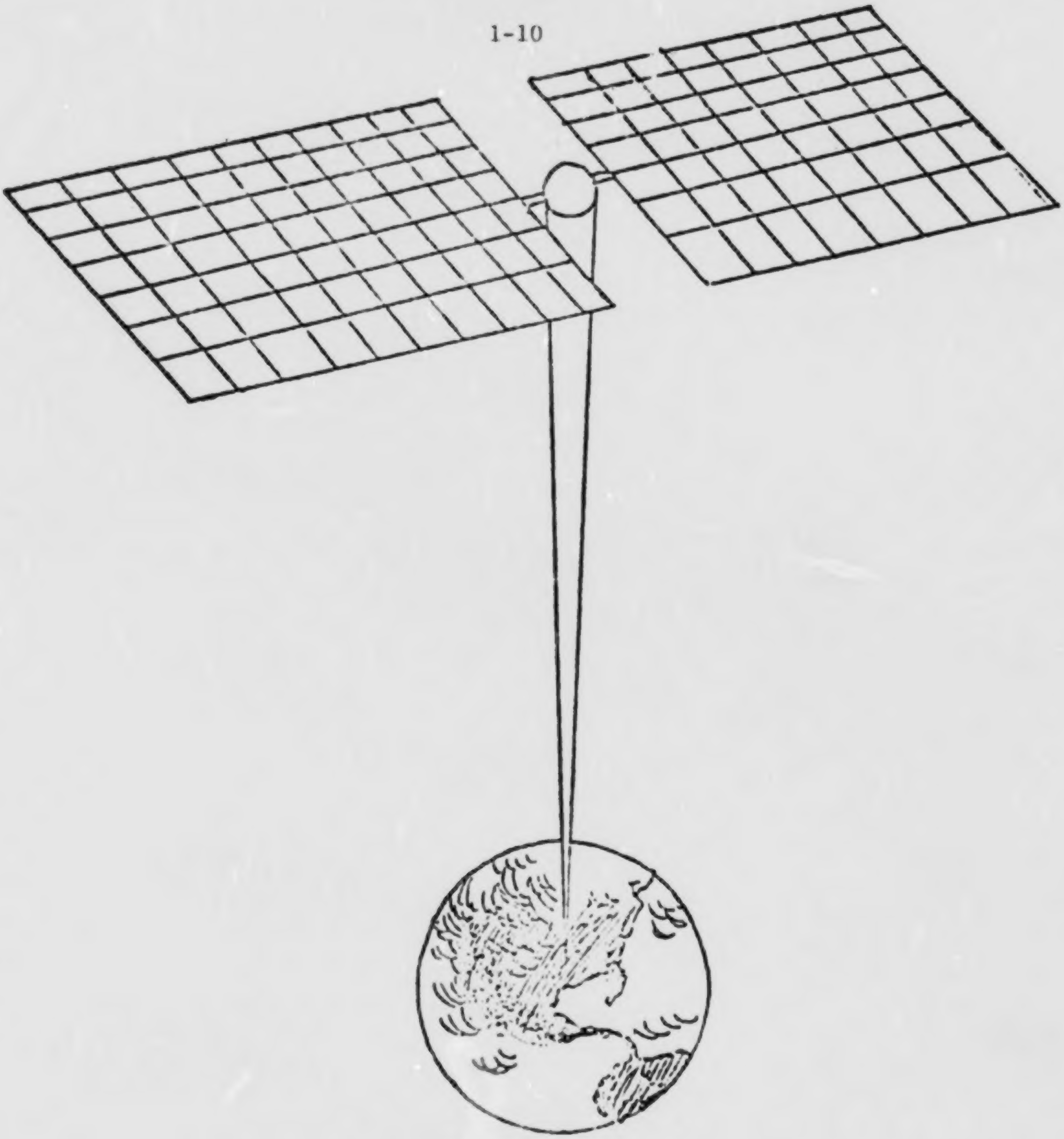
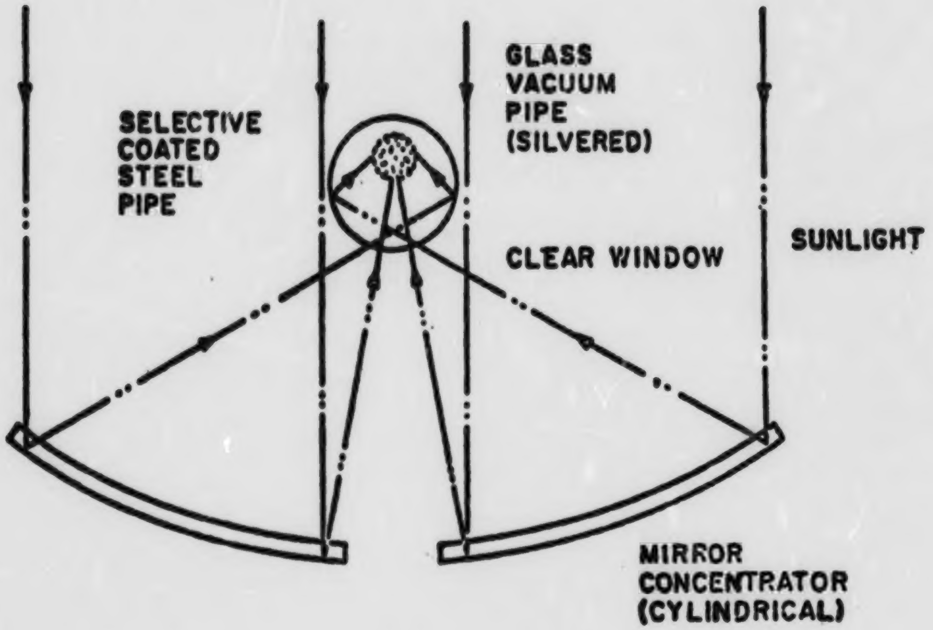


Figure 7: (Reference 7)

SOLAR COLLECTOR IN STATIONARY ORBIT has been proposed by Arthur D. Little, Inc. Located 22,300 miles above the Equator, the station would remain fixed with respect to a receiving station on the ground. A five-by-five mile panel would intercept about 8.5×10^7 kilowatts of radiant solar power. Solar cells operating at an efficiency of about 18 percent would convert this into 1.5×10^7 kilowatts of electric power, which would be converted into microwave radiation and beamed to the earth. There it would be reconverted into 10^7 net kilowatts of electric power, or enough, for example, for New York City. The receiving antenna would cover about six times the area needed for a coal-burning power plant of the same capacity and about 20 times the area needed for a nuclear plant.



CROSS SECTION DIAGRAM OF A TYPICAL COLLECTOR PANEL USING A CYLINDRICAL REAR-SURFACED MIRROR AS THE CONCENTRATOR

GLASS
VACUUM
PIPE
(SILVERED)
SELECTIVE
COATED
STEEL
PIPE
SUNLIGHT
CLEAR WINDOW
MIRROR
CONCENTRATOR
(CYLINDRICAL)

Figure 8: Typical One-Axis High-Temperature Collector

Reference 15

where solar energy can be obtained continually, and then sends the power to earth via microwaves (Figure 8). This would eliminate the need for large capacity energy storage.[7] Notwithstanding the long term promise of such proposals, at the present the problems are formidable.

1. Solar Photovoltaic Conversion

New Hampshire receives solar energy at an annual rate of about 135 watts/M^2. For a surface tilted south by 45° this value increases to about 160 watts/M^2. The best individual solar cells have a conversion efficiency of 12% to 15% at a room temperature of 20°C. In a panel, however, the light transmission of protective cover plates decrease with time due to UV-darking and dirt, the ambient temperature is higher, cell matching losses occur, etc., and the conversion efficiency will drop perhaps to about 8.5% or less. A "solar farm" with 8.5% efficiency panels facing 45° south would produce about 13.5 watts/M^2. Accordingly, to produce 1000 MWe would require about $75 \times 10^6 M^2$ (8.6 KM x 8.6 KM) of solar cells.

At the present time (1974) solar cells for space applications cost about \$40,000/$_M{}^2$ (\$300/watt × 135 watts/$_M{}^2$). There is no real consensus as to what could be achieved if produced on a large scale for terrestrial applications but \$5/watt with silicon appears to be possible within a few years.[1,8,9,10] With an appreciable R and D effort, using polycrystalline materials, such as copper sulfide and cadmium sulfide, perhaps \$1 to \$1.50 per watt might be obtained in a few years, with an ultimate cost as low as 40c to 60c per watt.[10] Small quantities of thin film Cu_2-CdS solar cells have been produced in pilot lines with efficiencies of 4 to 6 percent.[11] There fabrication processes appear amenable to mass production methods but so far yields have been low and the cells degrade.[12]

Projected cost estimates for panel structure designed to withstand the rigors of New England environment[12,14] and to protect solar cells range from \$20 to \$40 per square meter. Using a cost of \$30/M^2 for the panel structure and a 300 to 1 reduction from the present cost of solar cells (i.e. \$40,000/M^2 to \$133/M^2) we obtain a projected-lower-cost estimate of about $\$163/M^2$ ($\$30/M^2 + 133/M^2$) photovoltaic panels. With New Hampshire's annual solar input this is $12,000/KW.

2. Solar/Thermal/Electric Conversion Systems

In order to achieve high temperatures high enough to produce electricity by conventional methods, collectors that concentrate the solar flux are required. These collectors are relatively expensive because they must have low emissivity and low conduction losses.

One thermal conversion proposal[9,15] includes the use of one-axis steerable cylindrical parabolas. The collectors, as shown in Figures 8 and 9, would be east-west oriented and cover about 50% of the land area. Vacuum insulated heat collection pipes would be used at the focal points of the collectors. The energy would be stored as thermal energy in molten salt. Conventional steam turbine generators would be used to produce electricity. Typical parameters of a 1000 MW continuous output plant have been estimated as follows:[9,15]

Area of plant - 40 km^2
Area of collectors - 22 km^2
Outlet temperature of collectors - 500° - 600°
Collection efficiency - $\approx$ 60%
Thermal plant efficiency - $\approx$ 40%
Overall efficiency - $\approx$ 25%

The allowable construction budget for such a farm to produce power at a cost of 5.3 mills/kwh at a 25% conversion efficiency has been estimated in 1971 by Meinel[9] at $60/square meter for a site in the southwest having 330 clear days a year. Hottel and Howard[2] believe Meinel estimates assume overly optimistic optical and lifetime performance for selective coating and do not adequately account for degradation in optical transmittance in glass piping due to weathering and ignores pumping power required to circulate heat transfer fluids; they find an overall conversion efficiency of about 10% more reasonable.

Cost of utilizing solar energy will be much greater in New England than in the southwest because the collector array needs to be about twice as large. Moreover, the land costs are greater and the environmental conditions differ.

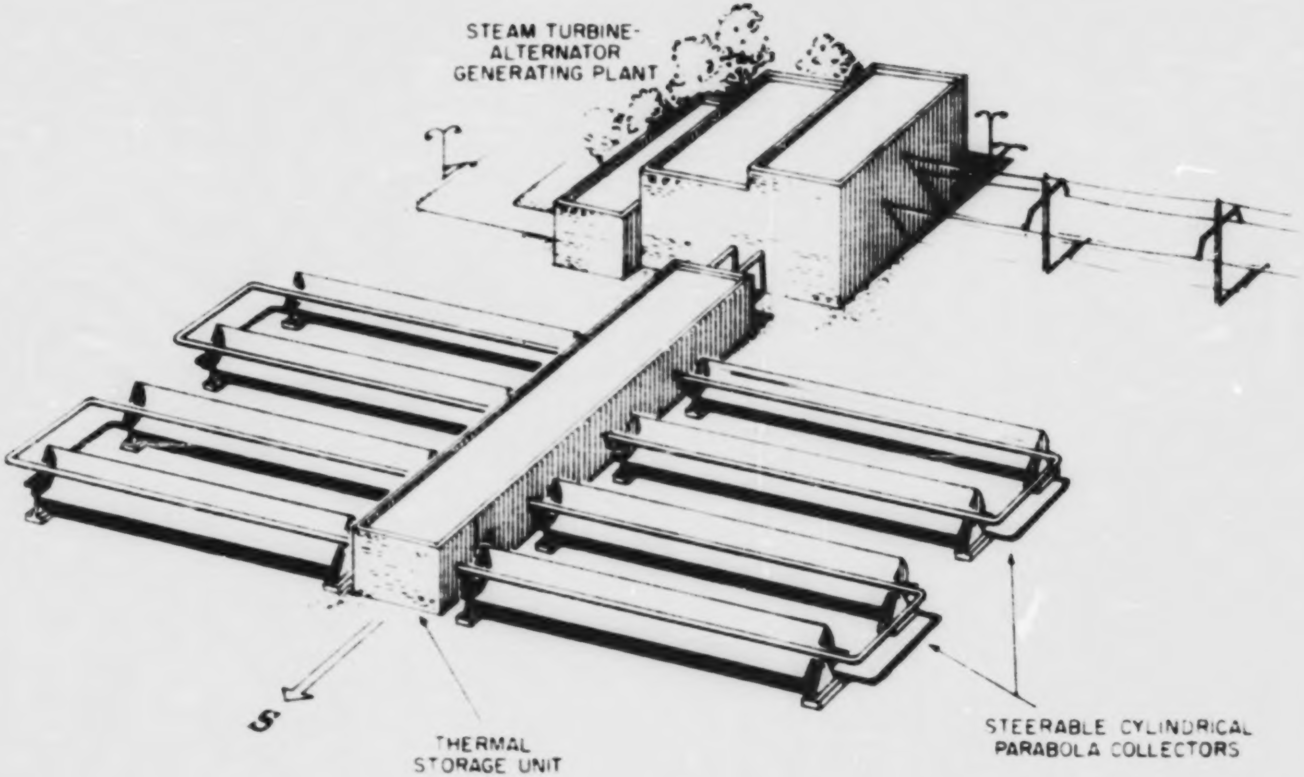

STEAM TURBINE-
ALTERNATOR
GENERATING PLANT
THERMAL
STORAGE UNIT
STEERABLE CYLINDRICAL
PARABOLA COLLECTORS
S

Fig. 9: Solar-Ground-Based Electric Generating Plant using Single-Axis Steerable Concentrators

Reference 9

In addition to the solar/thermal collection elements, a thermal storage subsystem will be required in order to satisfy energy generation deficiencies at night and on cloudy days. A long-term chemical storage system can be used to convert surplus solar power generated during the summer months into hydrogen or a hydrocardon fuel that can be burned in the winter to make up the deficiency in sunlight. Optimum design of energy storage subsystems is required to minimize the total amount of solar collector surface area required for a fixed, steady electrical generating capacity. The general relationship of both a short-term thermal storage and long-term chemical storage to the solar farm concept is shown schematically in Figure 10.

3. Energy Storage

Any practical solar energy system for large scale electrical power production must include efficient methods for both short- and long-term energy storage.

Short-term storage systems include chemical batteries, mechanical fly-wheels and thermal storage.[1] Table II shows the capability for candidate systems.

TABLE II

Sensible Heat Storage Materials

Material	Joules --- Per kg	------- Per Cubic Meter	M^3/kg
Water	1.6×10^5	1.6×10^8	1×10^{-3}
Rocks	0.4×10^5	0.5×10^8	$.8 \times 10^{-3}$
Glauber Salt ($Na_2SO_4 - 10H_2O$)	2.4×10^5	3.5×10^8	$.6 \times 10^{-3}$

Latent Heat Storage Materials

System	Joules --- Per kg	------- Per Cubic Meter	M^3/kg
Rocks Heated to 1000°C	1×10^6	1.68×10^9	$.6 \times 10^{-3}$
Salt Heated to 1000°C	1×10^6	2×10^9	$.5 \times 10^{-3}$
Chemical Storage			
Lead Acid Batteries	0.16×10^6	0.5×10^9	$.32 \times 10^{-3}$

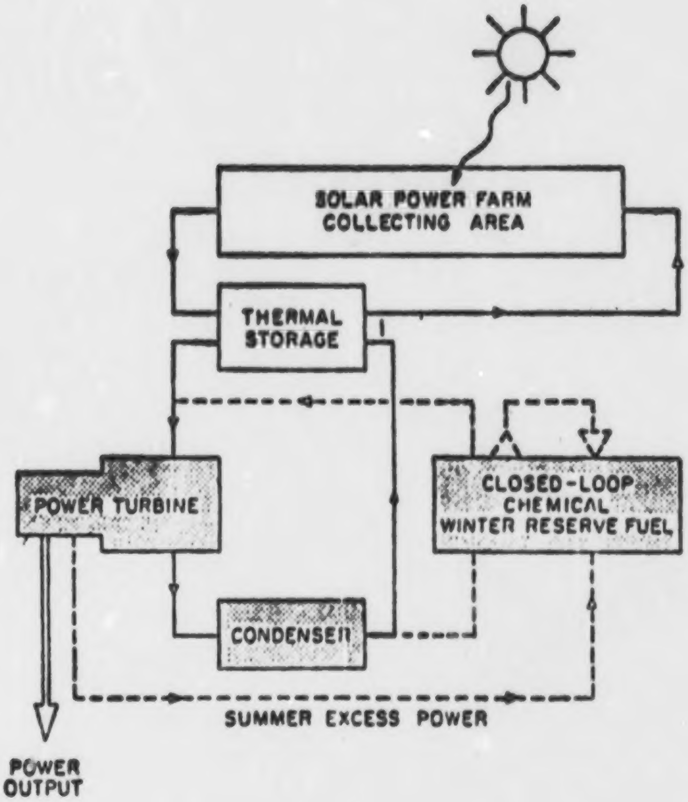

SOLAR POWER FARM
COLLECTING AREA
THERMAL STORAGE
POWER TURBINE
CLOSED-LOOP CHEMICAL WINTER RESERVE FUEL
CONDENSER
SUMMER EXCESS POWER
POWER OUTPUT

Figure 10

The Meinels' Proposal for a Solar Energy Form (Reference 9)

Because of energy losses, long-term storage must be in the form of fuel storage or pumped water. The most attractive fuel appears to be hydrogen.[16] Stored at high pressure and burned with oxygen, the energy storage capability of hydrogen is:[15]

TABLE III

Stored At	Joules/kg	Joules/M^3	M^3/kg
1 Atm. pressure	15.8×10^6	0.0014×10^9	11.3
100 Atm. pressure	15.8×10^6	0.14×10^9	.113
Liquid	15.8×10^6	1.12×10^9	.014

Electrolysis facilities can convert electricity into hydrogen at a rate of about 25 grams per kW-hr, which is equivalent to an efficiency* of 94%. This would mean that in one day a 1000 MWe plant operating continuously would produce 600,000 kg of hydrogen per day. Such an electrolysis facility is projected[14] to cost about $100 per kilogram hydrogen produced per day and when stored at 100 Atm. pressure would require about 6.7×10^4 M^3 of storage.

A source of pure water or equipment to capture and recycle the recombined water (result of combustion) is required.

O_2 is a dangerous gas, so special equipment and handling procedures are necessary.

5. Cooling Facilities

It seems unlikely that a 1000 MWe solar farm (14 kM x 14 kM) would be located near the ocean or a large lake in New Hampshire. Accordingly, a solar powered steam driven generator would be forced to use a cooling tower facility. The operation of the cooling facility is substantially the same with solar derived energy as with other fuels and therefore the size and cost should be comparable. "As yet no one has built a large dry cooling tower but estimates for a dry cooling facility for a 1000 MWe fossil fuel plant ($\eta = 40\%$) is $40 to $60 per kW and $60 to

---

* The efficiency for the production of hydrogen has been quoted from 65% to 94%.

$75 per kW for a nuclear fuel plant (η = 33%). The cost of a wet cooling tower for a 1000 MWe plant would be about 50 percent of dry unit cost."*

The actual cost depends upon many factors but data from 20 completed jobs show the cost scatter of $/kW is ± 40%.[22,23] The size required for a natural draft hyperbolic wet cool tower for a 1000 MWe plant is about 125 meters at the base with a height of 115 meters.[24]

C. Solar Augmented Space Heating and Cooling

Studies show that of all possible uses of solar energy, space heating and cooling has the highest probability of success in the near future.[12,13,14,17] Even though it is dilute and intermittent, enough solar energy strikes the roof of an ordinary home in New Hampshire to provide several times its annual heating and cooling requirements. The problem is to design systems that will economically capture and store the solar energy until it is needed.

In the past 25 years about 1000** solar heated houses and laboratory structures have been built with various combinations of collector designs, heat storage, heat distribution techniques and auxiliary energy supplies. This work, while generally successful, did not receive much attention because fuel cost has been low and suitable structural and coating materials have been expensive. These buildings were experimental and not readily adaptable to standard construction methods. Past experience has therefore demonstrated technical feasibility of solar-powered space heating but not its practical or economic viability.

Figure 11 illustrates the required components of a system for solar heating and cooling and Figure 12 shows a specific example. Using these diagrams as a reference, some important aspects of each component are discussed.

---

* Professor L. Glicksman

** Solar Heated Buildings: A Brief Survey. 9th Edition. May 27, 1975, W.A. Shurcliff, Cambridge, Massachusetts.

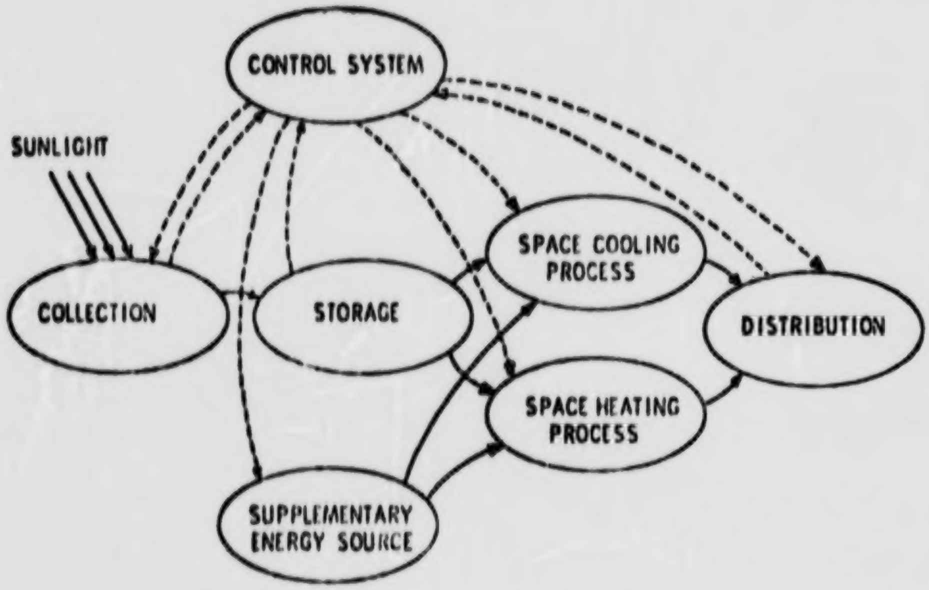

CONTROL SYSTEM
SUNLIGHT
COLLECTION
STORAGE
SPACE COOLING PROCESS
SPACE HEATING PROCESS
DISTRIBUTION
SUPPLEMENTARY ENERGY SOURCE

Figure 11: Required Components for Space Conditioning

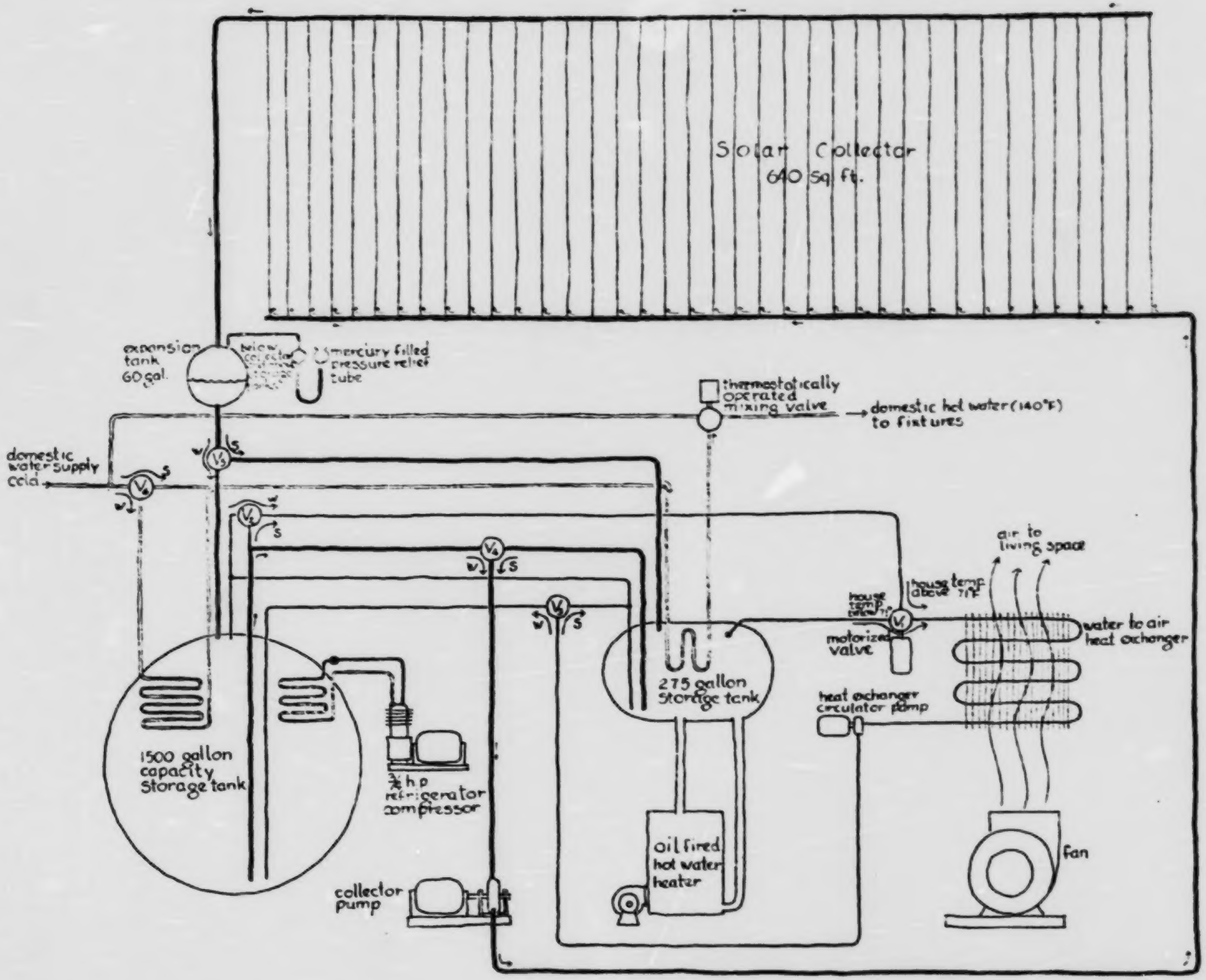

Solar Collector
640 Sq. ft.
expansion tank 60 gal.
mercury filled pressure relief tube
thermostatically operated mixing valve
domestic hot water (140°F) to fixtures
domestic water supply cold
V_1
V_2
V_3
V_4
V_5
V_6
S
W
house temp above 71°F
air to living space
motorized valve
water to air heat exchanger
275 gallon Storage tank
heat exchanger circulator pump
1500 gallon capacity Storage tank
¾ h.p refrigerator compressor
oil fired hot water heater
fan
collector pump

Figure 12: Example of Space Conditioning System

From: "Solar House IV," M.I.T. Press, Cambridge, 1958.

Solar Insolution in New Hampshire

The mean daily irradiance on a horizontal surface in selected geographical locations is shown in Table III. Day to day variations are large, with a typical range between peak and average of 1.5 to 1 in the winter, and 2 to 1 in the summer.[13,18,19]

The data of Table III show that Concord, New Hampshire, at the peak (July/July), receives solar energy at a rate (245 watts/$_M{}^2$) which is equal only to the yearly average rate in Arizona. Moreover, the 2 to 1 variation in the mean daily solar flux between summer and winter implies long-term (6 months) as well as short-term (daily and weekly) energy storage is required in order to fully utilize the available energy. It is interesting to note that the per capita consumption of energy for the USA for the year 1968 was about 3×10^8 Btu, which is equivalent to a constant power level of about 10 kW per person. The consumption for residential and commercial purposes were each about 20% of the total, or 2 kW per person. Accordingly, an average home in Concord, New Hampshire, assuming six people per home, would need a yearly average of 12 kW. To supply this amount even a December sun would require only a 30 feet by 30 feet area if all the available energy could be collected and stored.

Solar Collectors

Flat plate fluid (including air) collectors are useful in low temperature application up to a temperature of about 85°C of the fluid. They consist of a surface which is a good absorber of solar radiation and a means of removing the absorbed energy by allowing a heat transfer fluid (usually air or water) to flow over the absorbing surface. A major difficulty in collector design is due to the large area for heat transfer which causes heat loss and lower collector efficiency. To limit losses, the back of the collector must be well insulated. The losses from the upper surface are then suppressed by placing one or more transparent surfaces above the absorbing surface. By using materials such as low iron content glass, which are transparent to visible, and opaque to infrared energy, most of the solar energy reaches the absorber, yet the outward heat losses are minimized (greenhouse effect).

TABLE III

Mean Daily Insolation in Btu/$_M{}^2$-day and (Watts/$_M{}^2$)

Area	December		June		Entire Year
Horizontal Surface	Horizontal Surface	Tilted[1] Surface	Horizontal Surface	Tilted Surface	Horizontal Surface
Arizona	10,700 (130)		23,000 (340)		20,000 (245)
Entire U.S.	7,500 (90)		23,500 (290)		15,000 (185)
New England	4,250 (50)		17,000 (210)		11,500 (140)
Concord, N.H.[2]	5,100 (60)	11,200 (135)	20,000 (245)	19,300[3] (240)	12,500 (155)

1. Tilt angle equal to latitude, at local noon

2. June/July Average

3. In Concord, New Hampshire, in June, a surface tilted by 45° receives less power than a horizontal surface.

With present designs, flat plate collectors are capable of raising the temperature of heat transfer fluids to approximately 50° above the ambient temperature with an efficiency of 50%. A common method of raising collector fluid temperature is by increasing the number of transparent covers. Typically, one cover will give a 5°C to 34°C increase over ambient, two cover plates 35°C to 55°C, and three covers yield a rise of 55°C to 85°C. Other attempts to increase the temperature-efficiency performance include the use of selective coating of silicon on the absorber, low reflectance coatings on the transparent cover plates, better insulating materials around the back of the collector, and the use of honeycomb material to suppress convection losses. Drawbacks of many selective coatings are their instability (particularly at high temperature) and their high cost. Coating instability could be a problem. In addition, collector maintenance due to freeze-up, dirt,vandalism etc. is a serious consideration.

Current estimates for collector cost range from a low of $\$15/_{M}^{2}$ to over $\$100/_{M}^{2}$ with an average of about $\$45/_{M}^{2}$ using contemporary technology in large volume production.

Thermal Storage

A flat plate collector and a low temperature thermal storage system has the advantage that for space heating, the stored energy is directly usable in thermal form. The success of a thermal storage system is dependent upon the ability to store the thermal energy in a small volume with low loss.

The length of time over which heat is to be stored influences greatly the design and cost of thermal storage systems. Recent studies[2,20] of solar house heating show that the only systems that presently make sense economically are the partially solar heated house with one or two day storage.

Water and rocks (see Table II) are the most commonly used thermal storage media in solar heating systems. Water is plentiful, inexpensive, and has high specific heat. It works well for collectors with temperatures between 0°C and 100°C. Rocks can be used where air is used for energy transport between collector and storage. Generally, rocks have a lower specific heat (.2 to 1.0) and the storage volume is greater.

Estimates by Tybout and Lof[20] show that an optimum system is one with a ratio of about 200 lbs (25 gallons) of water per square meter of collector area. In a typical installation this gives a storage cost of about 50 cents per gallon of water.

Economic Considerations of Space Conditioning with Solar Energy

The cost of solar-thermal space conditioning can be divided into collector cost (i.e. the collector) and utilization cost (i.e. storage, pumps, controls, etc.).

According to one study[17] the collector cost is about $\$45/M^2$ when the collection efficiency is approximately 50%. With a life of 20 years and an interest on capital of 8%, cost for solar heat would be about $\$2.00/10^6$ Btu when (if) all the collected heat can be utilized.

The assumption that all the heat can be effectively utilized implies either an efficient long-term storage system or that demand for heat is uniform over the entire year. The requirements for constant demand is most nearly satisfied by a system that supplies a combination of domestic hot water, heating, and cooling.

Heat energy from coal costs about $\$2.00/10^6$ Btu, and from oil and gas about $2 to $3.50 per million Btu. "Therefore, under idealized conditions, the cost of low temperature solar heat appears to be approaching competitiveness."[17]

The cost of various storage, pump and control configurations have been studied using computer modeling techniques.[17,20] The results for an optimized least cost heating and cooling system indicate that utilization costs are about $\$30/M^2$ of collector area.

Other Aspects of the Use of Solar Energy for Space Conditioning

Due in part to the latitude, but more importantly the climatic conditions in New Hampshire, the use of solar energy is only practical as a supplement to conventional supplies. There are two reasons for this: (1) the extended periods of cloudiness and the attendent variations in the available solar energy make necessary a large amount of long-term energy storage, and (2) the seasonal variations in the available solar energy is out of phase with the heat load demand. As a consequence, without the use of auxiliary power, the solar collector and thermal storage systems are too large to be economically competitive.

- Studies indicate[2,13,17,20] that the best balance in the New England area is a system to produce from 33% to 50% of the total space conditioning load. Above this amount the required energy storage system is too large.

- Flat-plate collectors produce temperatures in a range from 0°C to 85°C which is compatible with the technology that is now used in hot water storage and distribution systems for homes.

- The bulk of the solar input occurs around noon (in New Hampshire, in December, 60% in three hours). Consequently, some thermal storage is necessary. These self-contained storage systems can be "charged" electrically during periods of off-peak loads and therefore can represent an effective means for cutting peak loads.

- Solar energy is more competitive when used with new buildings; one of the basic requirements is that solar-powered buildings must be as well-insulated as possible. It is also important to make maximum use of natural ventilation. Typically, new structures designed for solar space conditioning would emphasize energy efficiency. For example, walls and roof must be as small as is compatible with the space requirements. The outside skin of the building must be selected with good thermal performance. For air conditioning (cooling) purposes, all windows facing south should be equipped with moveable overhangs (one wants to accept solar heat in the winter), and all other windows sized to reduce heat exchange.

- In order for solar space conditioning to be effectively utilized, architectural concepts and construction practices will have to change somewhat from the recent past.[21] For implementation of this technology, means to overcome what are essentially social problems are likely to be necessary. Developing the technology is not enough because the fragmented building industry is traditionally slow to adopt new techniques. Also, solar assisted heating systems, despite their lower fuel cost, will entail higher initial cost, thus discouraging consumer acceptance. In any event, the slow rate of replacement of housing guarantees that it will be several decades before a new heating system will have a significant impact on total energy use.

In relation to the total energy consumed in New Hampshire, solar derived power is destined to remain small. Nevertheless, solar space conditioning can have a significant and favorable impact on electric utilities. There are several reasons for this: (1) the solar input is generally consistent* with the time of daily peak electrical demand; (2) the installation (first) cost of solar/thermal conditioning systems tend to be high while the first cost of electric heating systems tend to be low. Accordingly,** it is reasonable to combine the two installations using electrical energy as the auxiliary source of energy; (3) electrically powered hot water storage systems are easy to install, simple to operate and maintain; and (4) thermal storage units can be routinely charged at off-peak hours using base load facilities.

III. SUMMARY

Solar energy can be characterized as being identical to the radiation from a black body at 6000°K. Although its thermodynamic potential is high, solar flux is dilute and therefore solar collectors are large area devices.

The least developed technique for utilizing solar energy is the large scale production of electric power. Substantial capital cost reductions are necessary, perhaps by a factor of 10 using thermal conversion and a factor of 100 using photovoltaic conversion techniques. In order to achieve reductions of this magnitude, much work will need to be done to obtain low cost materials and material processing methods.

There is strong evidence that a large market exists for solar heating and cooling in residential and commercial buildings. Here little additional development effort is needed and future improvements in the performance and cost of roof collectors, etc. will only hasten the acceptance of solar augmented space conditioning. An important economic consideration is the fact that in any space conditioning system that utilizes solar/thermal energy there is a need for auxiliary heat energy in order to obtain a minimum-cost system. Because of this and the fact that most structures are installed with heating (and cooling) on a lowest-cost basis, a combination of solar/thermal and electrical auxiliary power appears to offer substantial benefits to both the consumer and utilities.

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* Generally consistent with the time of daily peak electrical demand means: peak solar input is between 10:30 a.m. and 1:30 p.m. during which the solar powered hot water storage is charged as much as it will be by, say, 2:00 p.m. It is available and can be used for space heating during the (5-6) p.m. daily customer peak for electricity.

** If solar/thermal space conditioning systems are to be used and the first-cost do tend to be high, then it is indeed fortuitous that it is easy to add an electrical heating element to the hot water storage of the solar system. The demand for electricity for this purpose can be made to coincide with the off-peak electrical hours of the bulk, central generation plant.

The present status of solar utilization is summarized by Table IV.

TABLE IV
Present Status of Solar Utilization

Technique	Research	Development	System Test	Full-Scale Demonstration	Model Plant	Commercial Readiness
Thermal Energy for Buildings						
Water Heating	X	X	X	X	X	X
Space Heating	X	X	X	X		
Space Cooling	X	X	X			
Combined System	X	X	X			
Electric Power Generation						
Thermal Conversion	X					
Photovoltaic						
Residential	X	X				
Commercial	X	X				
Ground Central Station	X					
Space Central Station	X					

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Monograph No. 2
MIT Energy Laboratory
WIND ENERGY

Wind Energy

Wind energy is not distributed evenly over the globe. On the average it is more plentiful in temperate and polar latitudes. Also, it is generally higher in coastal areas than inland. Wind velocity increases logarithmically with altitude up to the heights which one would consider in windmill (turbine) use and its flow patterns near the ground are strongly influenced by topography. New England is one of the earth's windy regions; the world's record wind velocity, 231 m.p.h., was recorded on top of Mount Washington on April 12, 1934.

Aeolian energy, as wind energy is sometimes referred to, is widely available, inexhaustible, clean and free. There is no question that it works; it has been used for centuries serving individuals or small group users. Like hydroelectric power it can be used directly for the generation of electricity without the large losses associated with thermal to mechanical energy conversion. But wind energy is intermittent, variable and is diffuse. Consequently, its utilization (like solar) [for bulk central power generation] requires a large number of collectors and adequate storage systems.

In New Hampshire large scale use of wind power for the generation of electricity is possible.[1] It is a windy region with abundant high mountains (forty-four over 4000 ft. elevation) near large population centers.

Large-Scale Electrical Power Generation

In order to be practical, large-scale wind-powered generating systems must have a good site location with a high mean wind velocity. The wind turbine must have an efficient aerodynamic design to operate over a wide range of wind speeds, and the electrical system must be properly integrated with established power grids. This requires careful voltage and frequency control of the power output which otherwise would be just as variable as the wind.

Site Location

The energy available is proportional to the cube of the wind velocity. The wind velocity increases and turbulence decreases with height above the surrounding ground. Mountain peaks, therefore, as well as high narrow ridges running in a north-south direction are good potential sites.[1] The repeatability of the pattern from year to year is also important. The best overall descriptor is a wind Velocity-Duration Curve. From these data and the characteristics of the wind turbine, the total utilization factor (kW hr/year generated per kW machine capacity) can be calculated. Other important site/wind factors are the frequency-distribution of wind direction, the vertical distribution of both the horizontal and vertical components of the wind velocity, the characteristics of gust fronts, etc.[1] These data are not now available for New Hampshire except for Mount Washington.

Large Wind Turbines

Wind has low energy per unit area. Because of this, wind turbines are necessarily large and must be designed to operate efficiently over a wide range of torque speed and load conditions. Present rotor designs are low solidity, high tip-speed, high stress structures.[2] Some of the technical design problems are: 1) determination of vibratory loads in presence of windshears resulting from earth boundary layers; 2) aeroelastic instabilities including effects of high coning angles and stall flutter; 3) control for optimum power output and speed regulation; 4) protection from high winds; and 5) icing on turbine or fan blades and on supporting structures.

The only large American wind turbine ever built and tested was in Vermont.[1] This machine was designed to produce 1.2 megawatts in a 35 m.p.h. wind with an overall efficiency of 30%. It had two 8 ton blades (175' tip to tip), one of which failed from metal fatigue.

The energy in a wind stream is proportional to $\frac{1}{2}$ PAV^3 where P is the density of the air, A is the area, and V the wind velocity. The maximum power that a windmill can extract from an air stream is 59.3%[3] of the kinetic energy passing through the area swept by the blades. Windmills of good aerodynamic design can achieve about 70% of the theoretical maximum, i.e., 41.5%.

The output from a windmill increases linearly with the area, or as R^2 ($A = \pi R^2$), while blade weight increases as R^3. This "square-cube" relationship limits the maximum size of a windmill because of the diminished power to weight ratio.

With available materials, the largest size windmills presently envisioned are about 200' tip to tip, mounted on a tower about 150 feet high. Studies[1,2,4] indicate that such a windmill (located at a suitable site) would be a nearly optimum design and could produce up to 10MWe at a cost between $350 per kW and $400 per kW of installed capacity. To generate the equivalent output of a single fossil fuel or nuclear MWe plant would require a hundred of these windmills.

Windmill Control and Integration with Existing Power Grids

There are two ways to design a wind turbine to operate efficiently over a wide range of wind speeds. One is to allow the windmill to operate at a constant blade-tip to wind speed ratio and design the load to absorb power as the cube of the wind speed. The other is to change the blade pitch, thereby varying the torque but keeping the blades at a constant rpm. The constant-pitch, variable-speed system is simpler mechanically but requires a frequency-controlled alternator. Direct nonsynchronous machines, where the variable ac is converted to dc and back to ac again, using batteries for the intermediate storage, have also been proposed.[2,5] This type of conversion has the advantage of decoupling the variable frequency windmills from the mixed power grid.[2]

In order to avoid double conversion losses, it is important to utilize wind energy on-line as much as possible. On the other hand, in order to extract the maximum average energy available from an intermittent and variable wind system, it is necessary to have an energy storage facility.

Candidate storage systems include: Secondary batteries which have the advantage of storing at an overall efficiency of about 75%. Energy densities are from 10 to 100 watt-hours/pound and 30 to 100 watts per pound with a battery life of about five years. The cost is estimated[2] at about $80 per kilowatt hour. The use of battery storage systems are now being studied from critical materials standpoint (lead and zinc).

Pumped water storage systems are quoted at 67% efficiency and at a typical cost of $180 per kilowatt hour.[2]

Compressed air storage is about 67% efficient and would cost about $100/kW of installed capacity.

A system for the electrolysis of water to produce hydrogen is a popular concept.[1,2,6] Cost estimates vary from $100 to $250 per kilowatt of installed capacity.[9] One problem is the availability of suitable pure water for electrolysis.[1] The feasibility of storing hydrogen in the gaseous state along with the problem of hydrogen induced embrittlement of metals is also being studied.

The availability of water and the need for high pressure storage has led some to propose an off-shore-wind program with windmills out in the ocean off the coast of New England.[6,10] The arguments are that the wind is more consistent, there is abundant water for electrolysis, and the hydrogen can be securely stored in deep water at very high pressure.

Considerable research is required to determine the effects of seasonal variations in wind direction, velocity range, gusts, and sea state. A salt water/atmosphere environment is very hostile to machinery and electrical equipment. The combined effects of corrosion and hydrogen embrittlement on the hydrogen storage tanks must be predictable.

Off-shore oil drilling and production platforms for anchorage in depths of water up to 300 feet have been in use for some time. A windpower system designed and constructed to survive the combined forces and stresses due to ocean currents (surface and sub-surface), wind gusts, yawing due to attempts to remain orthogonal to wind direction, and the Coriolis force (effect of earth rotation) is a significant engineering task.

Studies Concerning Small Windmill Systems

Before 1950, when rural electrification became widely used, about 50,000 small windmills were used in the midwest. The enactment of the Rural Electrification Act brought low cost, reliable central generating station electricity to the farms.

It is interesting to note that wind energy is now being evaluated as a supplemental fuel in megawatt-size wind turbines, and medium size (100kW) installations that may also combine water electrolysis and fuel cells for commercial power production.[2]

Consideration of the use of windmills to produce supplemental energy for individual residential and small commercial applications is also growing. However, such wind systems, complete with tower structure, windmill, storage batteries, and dc to ac inverters are available with ratings of 10 to 1000kW-hour/month at a cost of about $1,500/kW capacity.[7] In addition, the owner would either have to be technically competent or hire persons to maintain such systems.

Results from on-going research and development efforts appear to offer much improved performance by simpler systems. Both the National Science Foundation and the Energy Research and Development Agency are funding R & D efforts, albeit the total dollar funding is considered by many to be too low. Horizontal-Axis Wind Turbine Studies include:

- NASA, 125' diameter, 100 kW-turbine design emphasizing a low-cost technology. This system is designed to operate directly into a power system grid without storage and is scheduled to be operational in July, 1975.
- Oklahoma State University, Bicycle-wheel Turbine; high-lift/low-drag structure designed for light weight and low cost. Early results indicate the efficiency is close to the theoretical limit of 59%.
- Princeton University, 25' diameter Sailwing. The blades have a cross section similar to a high performance glider wing giving maximum lift and minimum weight. Both Grumman and Fairchild are working with the design. Results to date are

outstanding, the lift/drag ratio is 20:1, the complete wing weighs only 44 pounds and has survived 160 knot wind tests.

The Darrieus Vertical-Axis wind rotor was invented in 1931. The vertical-axis configuration has the advantage that its operation does not depend upon the wind direction and therefore it has a high potential for high efficiency in rapidly varying wind directions. This, together with the advantage that the output is at the bottom of the structure, simplifies the design, reduces cost and allows wind power to be used in more turbulent wind patterns.[2,8] A disadvantage is that the device is supported only at the base and the foundation and bearings are subject to high bending forces.

Summary

It appears that the earliest application of modern wind power will be, as it has been in the past, to meet individual or small community needs supplementing the more conventional sources. This allows efficient utilization of the distributed nature of wind energy. There are a number of active research programs in this area.

Conceptual designs for large central power plants have been done and cost estimates made. We have little practical experience with even the components of such large systems. The construction of large plants would involve substantial risk. No environmental impact analyses have been made.

Present cost ranges appear to be as follows:

Wind Turbine: $350 - $400 per kW installed capacity.

Storage:

Pumped Water: $180 - $220 per kilowatt hour

Electrolysis of Water: $100 - $250 per kilowatt installed capacity.

Hydrogen Storage (High Pressure System): $75 - $110 per kWh - day.

Batteries: $80 - $100 per kilowatt hour.

Compressed Air: $80 - $100 per kilowatt hour.

System Integration and Control:

In order to make a realistic estimate of cost for the integration and control of a large windmill system into the existing power system, it is necessary to know in fair detail the quantity or quality of the wind in New Hampshire. The trade-offs are complex; for example, if the windmills are clustered in one region, the cost of crew housing, power transmission, etc. are reduced. On the other hand, if 200 or 300 windmills are widely dispersed, the total output power produced by the "wind-grid" would probably be more even and therefore require less energy storage capacity, etc. Maintenance costs for the windmill would be increased by its remoteness; however, the windmill is less complex than some other systems, etc. As a guess, a first-cost of $100 per kWh installed capacity for system integration and control, along with 5% per year maintenance, might be reasonable.

In order to develop a dispersed wind energy powered electric generation utility, a number of issues, actions and developments must take place.

1) The state or region must be surveyed for average, peak, and gustiness of winds, preferably over a span of a few years.
2) Assembledge of data on icing conditions and snow fall amounts.
3) Determination of site availability, access to and from for construction, maintenance and coupling to regional electrical grid.
4) Selection of optimum size and support structure for each site.
5) Establishment schedules for that portion of electricity obtained from wind energy.

The time necessary to accomplish the above for a system that would deliver 1000 megawatts average would be in the order of ten to fifteen years.

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Monograph No. 3
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OCEAN THERMAL ENERGY CONVERSION

Sea water is always colder at depth.* Surface waters are warmed by capturing solar energy and storing it. The deeper one goes the colder it is, and often approaches the freezing point. The possibility of using heat engines, operating on the temperature difference between surface and deep waters to produce electricity for direct use or for production of fuel, perhaps hydrogen, excites the interest of scientists and industrialists alike.

The maximum absolute temperature and the maximum temperature differential of surface and deep waters varies with latitude. In the region between 20°N and 20°S the differentials encountered are sufficient[1] (20°C) to vaporize other working fluids (freon, ammonia, etc.). The lower temperature behavior characteristics of such fluids permit one to operate turbines and hence generate electricity.[8] (see Figures 1, 2 and 3).

Between the Tropic of Cancer 23°N and the Tropic of Capricorn 23°S, the ocean's surface stays almost constantly at 25° because of the heat collected from the sun and heat lost due to evaporation and other processes.

This warm water moves toward the poles (the Gulf Stream is one ocean current in the Atlantic Ocean) where it melts the ice. The water of the melted ice is very cold, hence much denser than the surface water. The cold water sinks to the ocean floor where it moves towards the equator and upwells to replace the warm surface water that has moved towards the poles. In the tropics the water at depths of 3000 feet is about 5°C. It is in this region only that solar/sea electric power generation is possible.

The efficiency of an ocean thermal generating plant would be very low. The maximum thermodynamic efficiency for a temperature differential of ten to twenty degrees for the working fluid, which corresponds to an

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*There are situations where this may be so, but are not pertinent to this discussion.

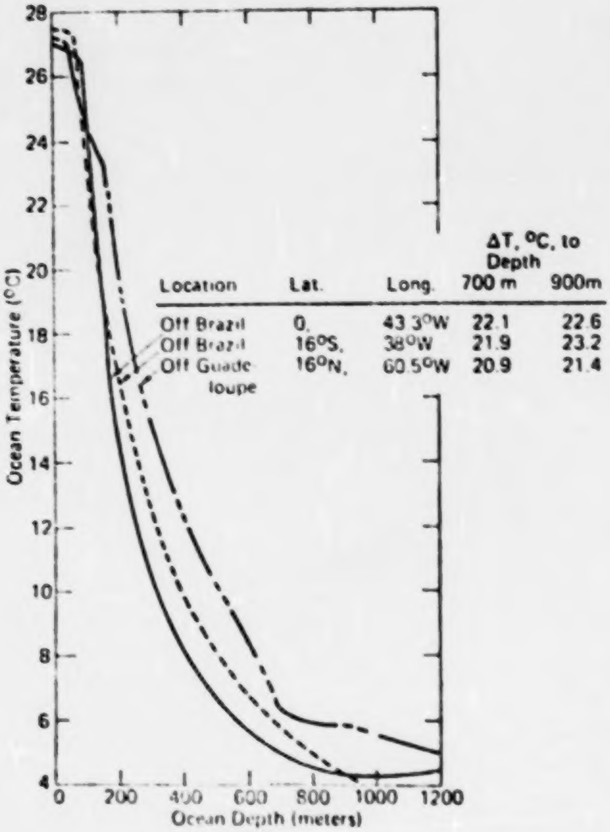
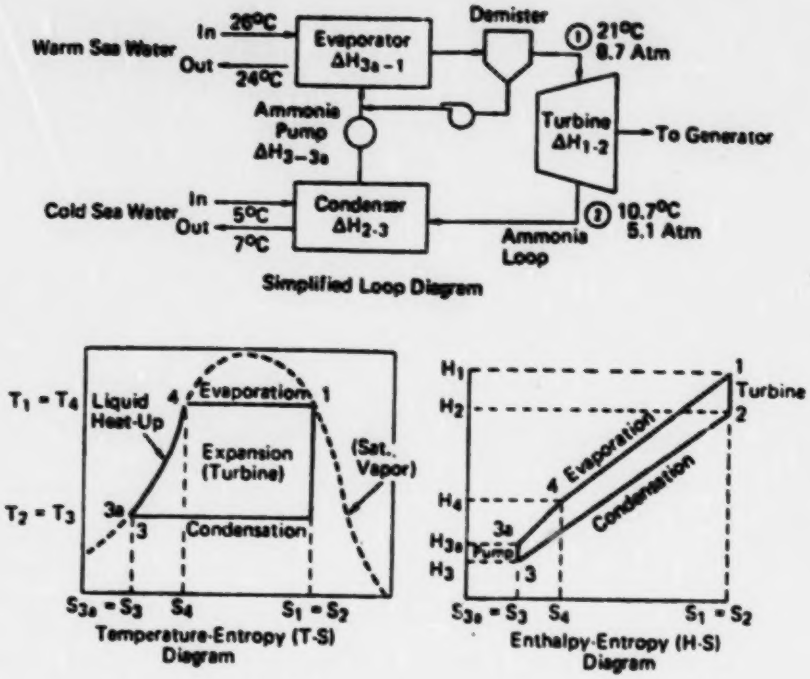


Figure 1: Thermoclines in the Tropical Atlantic Ocean

Reference 8


Warm Sea Water
In
26°C
Out
24°C
Evaporator
ΔH3a-1
Demister
① 21°C
8.7 Atm
Ammonia
Pump
ΔH3-3a
Turbine
ΔH1-2
To Generator
Cold Sea Water
In
5°C
Out
7°C
Condenser
ΔH2-3
② 10.7°C
5.1 Atm
Ammonia
Loop
T1 = T4
Liquid
Heat-Up
4
Evaporation
1
Expansion
(Turbine)
(Sat.
Vapor)
T2 = T3
3a
3
Condensation
S3a = S3
S4
S1 = S2
H1
H2
H4
H3a
H3
1
Turbine
2
Evaporation
Condensation
4
3a
Pump
3
S3a = S3
S4
S1 = S2

Simplified Loop Diagram

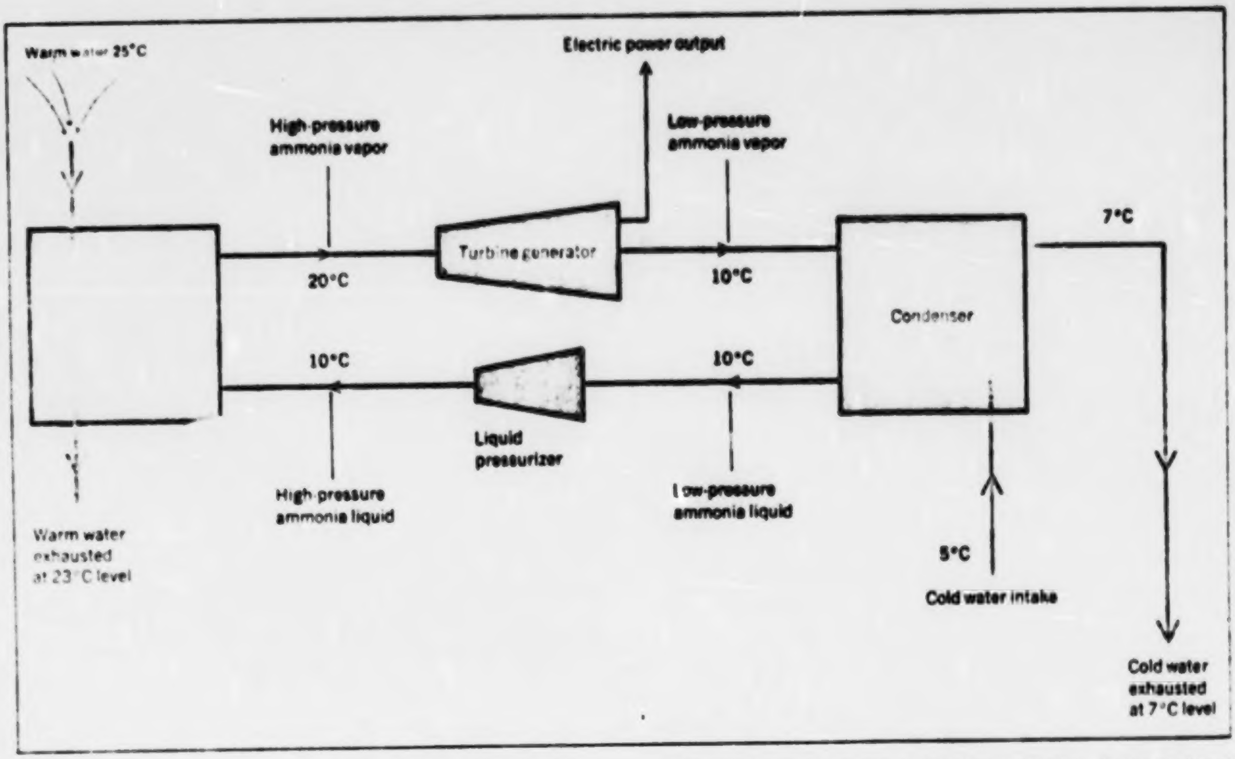
Temperature-Entropy (T-S) Diagram

Enthalpy-Entropy (H-S) Diagram

Fig. 2 Simplified loop diagram (for tropical ocean temperatures and ammonia working fluid), T-S diagram, and H-S diagram for the closed-Rankine cycle, Ocean Thermal Energy Conversion (OTEC) plant.

Figure 2

Reference 8


Warm water 25°C
Electric power output
High-pressure ammonia vapor
Low-pressure ammonia vapor
Turbine generator
7°C
20°C
10°C
Condenser
10°C
10°C
Liquid pressurizer
High-pressure ammonia liquid
Low-pressure ammonia liquid
Warm water exhausted at 23°C level
5°C
Cold water intake
Cold water exhausted at 7°C level

Schematic diagram of a solar sea power plant. Ammonia is assumed to be the working fluid in the boiler, turbine and compressor in this example, but more recently developed refrigerating fluids, such as the freons, might be preferable. The quantity of water passing through the boiler is comparable with that passing through a hydroelectric plant with the same output.

Figure 3

Source: Zener, Clarence, "Solar Sea Power," Physics Today, pp. 48-53, January 1973.

ocean surface/deep temperature difference of 21°C is about 3 percent. Practically, the efficiency obtainable would be no more than 2 to 2.5 percent. This, in itself, is not a serious drawback; the temperature difference (fuel) is free. The low efficiency is important because the size of the plant would be greater than any other type of electric power plant. Large amounts of water must be circulated through the heat exchanger. The costs need not necessarily be greater because the pressure differentials are not great and boilers, heat exchangers and turbines need not be constructed so as to withstand 1500 pound differentials. Solar sea systems can be designed for pressure differentials of only a few pounds. It is the cost-per-kilowatt hour of electricity produced that is most important.

In 1929 a Frenchman, George Claude, built[9] an ocean thermal gradient power plant in Cuba that produced 22 kW of useful power. The system used sea water as the working fluid which proved to be inefficient because of its low vapor pressure. The system, as a competitor to fossil-fueled plants, was an economic failure at that time.

Anderson and Anderson[1] carried out a detailed study of an ocean thermal power plant in 1966. Their studies resulted in an estimate of capital cost of $165/kW for a 100 MW sea power plant. At that time, the estimate was comparable to the cost of a conventional fossil-fuel plant.

Fossil-fuel plants currently cost $350-400/kW and nuclear reactors are now approaching $500/kW in capital cost. Even if one allows for inflation, ocean thermal power plants are increasingly attractive. Avery's estimates for the cost of a 1000 megawatt (electrical) plant are reproduced as Table 1.

Rust[3] estimates a capital cost of approximately $560 per kilowatt for a solar sea power plant. Hence, a 1000 megawatt power plant would cost 560 million dollars, about twice the estimate of Avery.

Rust[3] estimates that the amount of sea water required to produce 1000 MWe would be 5.6×10^{10} pounds per hour (about a hundred million gallons per minute, or over one-third the flow of the Mississippi River) through the condenser. The separation between the inlet ducts for these

ELECTRIC POWER COST AT OTP

CONSTRUCTION COST 1000 MW PLANT	=	$263M	169M
FIXED CHARGES AT 11.8%		$ 31M	20M
INCLUDES COST OF MONEY	8.2%		
DEPRECIATION & REPLACEMENTS	1.2%		
INSURANCE	.2%		
INCOME TAXES	2.2%		
OPERATING COSTS		$ 10M	9M
TOTAL ANNUAL COST		$ 41M	29M
COST MILLS/KWH		4.67	3.3

Table I

Source: Avery (2)

10/28/74

two systems would be in the order of 4000 feet. To move these amounts of water over these distances would require considerable energy. Pumping energy requirements could be reduced with large cross section ducts and heat exchangers.

The area of the ocean between latitudes 10° north and 10° south around the earth is about 30 million square miles. The average insolation energy on the surface is about 20 watts per square foot. One may, then, consider this the heat replacement rate. At an extraction efficiency of 3%, 60 square miles 0.0004% of that tropical ocean area, where the depths exceed 2000 feet, would support a 1000 megawatt electric power plant.

A solar sea power plant need not be used to produce only electricity. The warm surface waters in the tropics are often exhausted by the high rate of photosynthesis, of nutrients that are necessary for marine life. The cold water that upwells brings with it large quantities of bottom nutrients and no organisms which produce disease in humans, predators and parasites in shellfish. This formerly bottom water can be used in mariculture (artificial forms of sealife that can be eaten by man or introduced into his food chain). In addition, large quantities of fresh water could be produced for shipment to the shore communities. The combined revenues from power generation, mariculture and desalination, could make solar sea energy development very beneficial.

Ammonia is manufactured for use in the production of chemicals and other products. The principal use is in fertilizers. In the U.S., natural gas is the feedstock for the ammonia factories. Natural gas is in critical short supply. Production of ammonia at an ocean thermal plant would require only nitrogen from the atmosphere and hydrogen from the sea water. Since the demand for fertilizers will continue to increase, the economic attractiveness of such an adjunct to an Ocean Thermal Energy Conversion (OTEC) plant will increase.

On one hand OTEC is very attractive economically; on the other hand, a great expanse of the sea and nearby estuaries would be involved. Paskausky[4] suggests that the environmental impact by the redistribution of dissolved oxygen, nutrients, isotherms and corrosion products needs thorough investigation because oceanic fauna are much more sensitive than estuarine fauna.

On 13 July 1974, the Solar Energy Task Force of the Project Independence Blueprint Study issued a report on Ocean Thermal Energy Conversion. It describes a program which is designed to "establish the technical, economic, and geopolitical feasibility of large-scale floating power plants capable of converting ocean thermal energy into electrical energy, leading to the commercial utilization of such plants and the production of significant amounts of energy."

The OTEC intends to initiate construction of a proof-of-concept experiment very early in the 1980's. This is expected to lead to a 100 MWe demonstration plant before the middle 1980's and a total production capacity of 1000 MWe by the mid-1980's.

Based on certain assumptions, two scenarios are postulated for availability of ocean thermal powered, electric generating plants:

I. "Business-as-Usual"

1985	1,000 MWe*
1900	4,000 MWe
1995	16,000 MWe
2000	65,000 MWe

II. "Accelerated" (government incentives, etc.)

1985	1,000 MWe
1990	6,300 MWe
1995	40,000 MWe
2000	260,000 MWe

These estimates are based on the belief that the technology required for OTEC is relatively low-level and only a few scientific or technical breakthroughs are required.

---

* MWe - megawatts of electricity

The authors of the "Blueprint" further acknowledge that environmental consequences cannot be predicted before at least a pilot plant is built. Also, siting limitation associated with availability of thermal resource and of suitable ocean conditions, plus regulatory problems, such as freedom-of-navigations and law-of-the-sea considerations may impose certain limits to the availability of ocean areas for this application.

Such problems as biofouling of components and subsystems, anchoring, mooring, dynamic positioning of materials compatibility and corrosion, construction system and methodology for power plant installation and maintenance are considered "avoidable or corrective." Means of transporting (including conversion and storage, as necessary) large amounts of power generated at a distance at sea is not discussed.

In view of the complete lack of experience in the generation of electricity from solar sea thermal differential, the wide range of capital costs (estimates both for the plant and the transmission lines to the shore) and the nature of the problems anticipated, the timetable of Project Independence Blueprint for OTEC appears rather optimistic.

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2) Avery, William H., Ocean Thermal Power, a special presentation to U.S. Senator Mathias and Mr. J. Sawhill of the FEA at the Applied Physics Laboratory of the Johns Hopkins University, October 30, 1974.

3) Rust, James H., "More on Solar-Sea Power," Physics Today, pp. 9-13, September 1973.

4) Paskausky, David F., "Solar Sea Power Impact," Physics Today, letters p. 15 and 115, January 1974.

5) Othmer, D.F. and Roels, O.A., "Power, Fresh Water, and Food from Cold, Deep Sea Water," Science Volume 182, pp. 121-125, October 12, 1973.

6) Zener, Clarence, "Solar Sea Power," Physics Today, pp. 48-53, January 1973.

7) Metz, William D., "Ocean Temperature Gradients: Solar Power from the Sea," Science Volume 180, pp. 1266-1267, June 22, 1973.

8) Avery, et.al., "Tropical Ocean Thermal Powerplants and Potential Products," American Institute of Aeronautics and Astronautics and the American Astronautical Society Conference on Solar Energy for the Earth, AIAA Paper No. 75-617, 21 April 1975, New York, New York 10019.

9) Claude, Georges, "Power from Tropical Seas," Mechanical Engineering Volume 93, No. 10, 1971, pp. 21-25.

William J. Jones
December 1, 1974
Amended, June 1975
William J. Jones

Monograph No. 4

MIT Energy Laboratory

GEOTHERMAL ENERGY

In man's quest for low cost energy, geothermal energy has met some of his requirements for several thousand years. Hot springs have been contained or the waters channeled to baths, to assist in agriculture, to move machinery directly and, most recently, to generate electricity. As a substitute for fossil and nuclear fuels, it beckons consideration.

Geothermal energy, in the broadest sense, is the natural heat of the earth. One may consider the earth as consisting of a core of molten material at a temperature of 4000°C with ever-increasing layers of material (like skins of an onion) between it and the earth's surface. The temperature decreases as one approaches the surface of the earth. The heat at the center flows out to the surface at a low rate (1.5 calories per square centimeter per second).

The "layers" referred to above are not constant in thickness all over the volumes that they enclose. In addition, there are "breaks," "depressions," and "bumps" which result in an uneven outward flow of heat at certain spots and hence great differences in near surface temperature. The extreme case is an active volcano where there may seem to be a hole or passage from the center core radially outwards to the surface.

A very crude section of the earth is shown in Figures 1 and 2.[11] In the outer layer, the crust is composed mostly of rock formations. The base of the crust is about 10 to 50 Km (6-10 miles) below the surface of the earth, with the smaller figure applying under the oceans. As we go down into the earth, the temperature rises by about 10° to 20°C per Km so that temperatures in the crust can rise to as high as 1000°C (1800°F).[12]

Frequently "hot spots" exist where the unevenness of the layers or breaks in some of the "layers" below them allow more heat to flow from the core so that much higher temperatures occur at that place than exist elsewhere beneath the earth's surface at that depth.

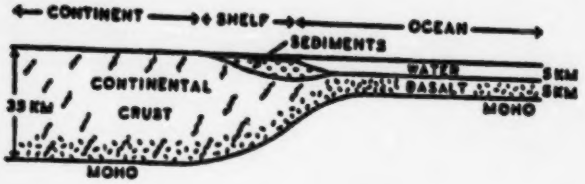
CONTINENT
SHELF
OCEAN
SEDIMENTS
WATER
5 KM
BASALT
5 KM
CONTINENTAL
CRUST
35 KM
MOHO
MOHO

Figure 1: Schematic section through earth's crust at an inactive coastline, such as that of eastern North America.

Reference 11

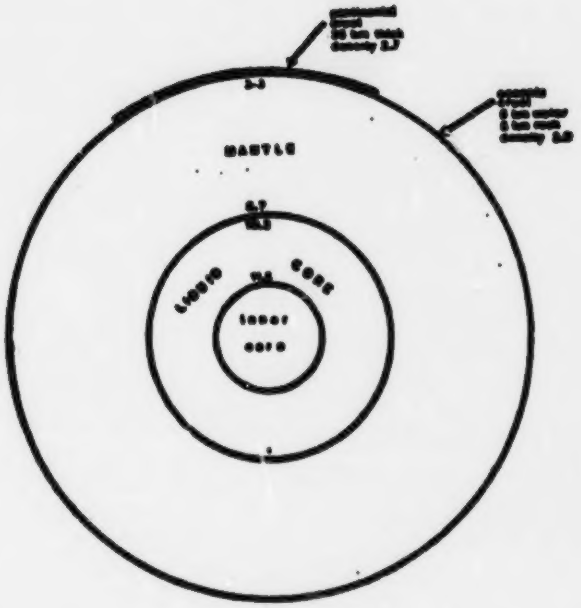
MANTLE
LIQUID
CORE
inner
core

Figure 2: Crust, mantle and core. The figures are densities in g/cm^3.

Reference 11

There are locations where the rain (surface) water oozing down through the outer "layers" comes in contact with these "hot spots" (Figure 3). The water is heated, may turn to steam, and force its way to the surface. Depending upon the temperature of the "hot spot" and the path to the surface, the water may emerge as steam, hot water, or a mixture of both. The heated water, at depth, is under pressure and may "flash" to steam upon approaching the surface where the pressure is less.

If seismic and geophysical data so indicate, holes are drilled down towards the irregularities in the contours to "hot rocks." Water is pumped down the holes, and upon contact with the high temperature material, turns to steam and transfers the heat to the surface.

Geothermal resource areas are: 1) areas on the surface of the earth where steam or hot water emerge, or 2) where artificial stimulation is possible because of the "bumps" which are close enough to the surface (less than 9000 feet) to be reached by drilling.

These areas are not evenly distributed over the earth's surface. The west, Alaska and the Virginias are the only such places in 49 of the United States, as Figures 4 and 5 show. Figures 6 and 7*show world-wide distribution. In Hawaii the Center for Science Policy and Technology assessment of the Governor's office is considering a plan for using the geothermal energy in that state. It is believed that deep-lying hot rock might be used to create electricity-generating steam.

The Hawaiian Islands are volcanic in origin and there are a number of active and dormant volcanoes. The most probable source is on Hawaii, where University of Hawaii scientists are seeking evidence of steam or super-hot water.

New England and the Midwest are almost completely devoid of any opportunities to develop geothermal energy. This is not to say that one cannot obtain geothermal energy in New England. It is the depths to which one must drill and the kinds of materials that will be encountered on the way down which make it very unlikely that it will ever be done, even though geothermal energy may be considered "free." In addition, the energy necessary to pump cold water down and then up again after it has been heated may be greater than that extracted.

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* Figures 4-7 are from Armstead, Christopher, editor, "Geothermal Energy: Review of Research and Development" UNESCO, Paris, 1970.

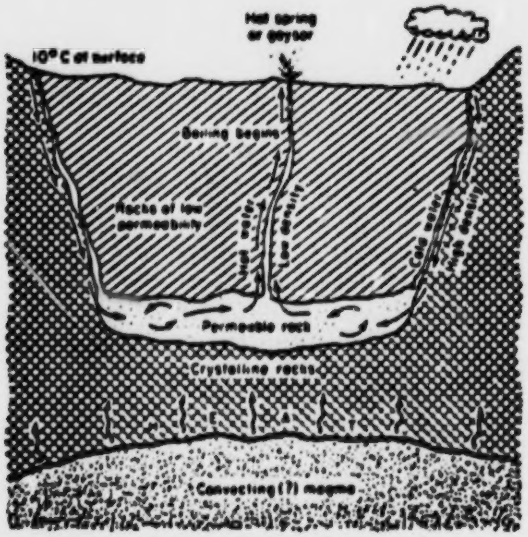
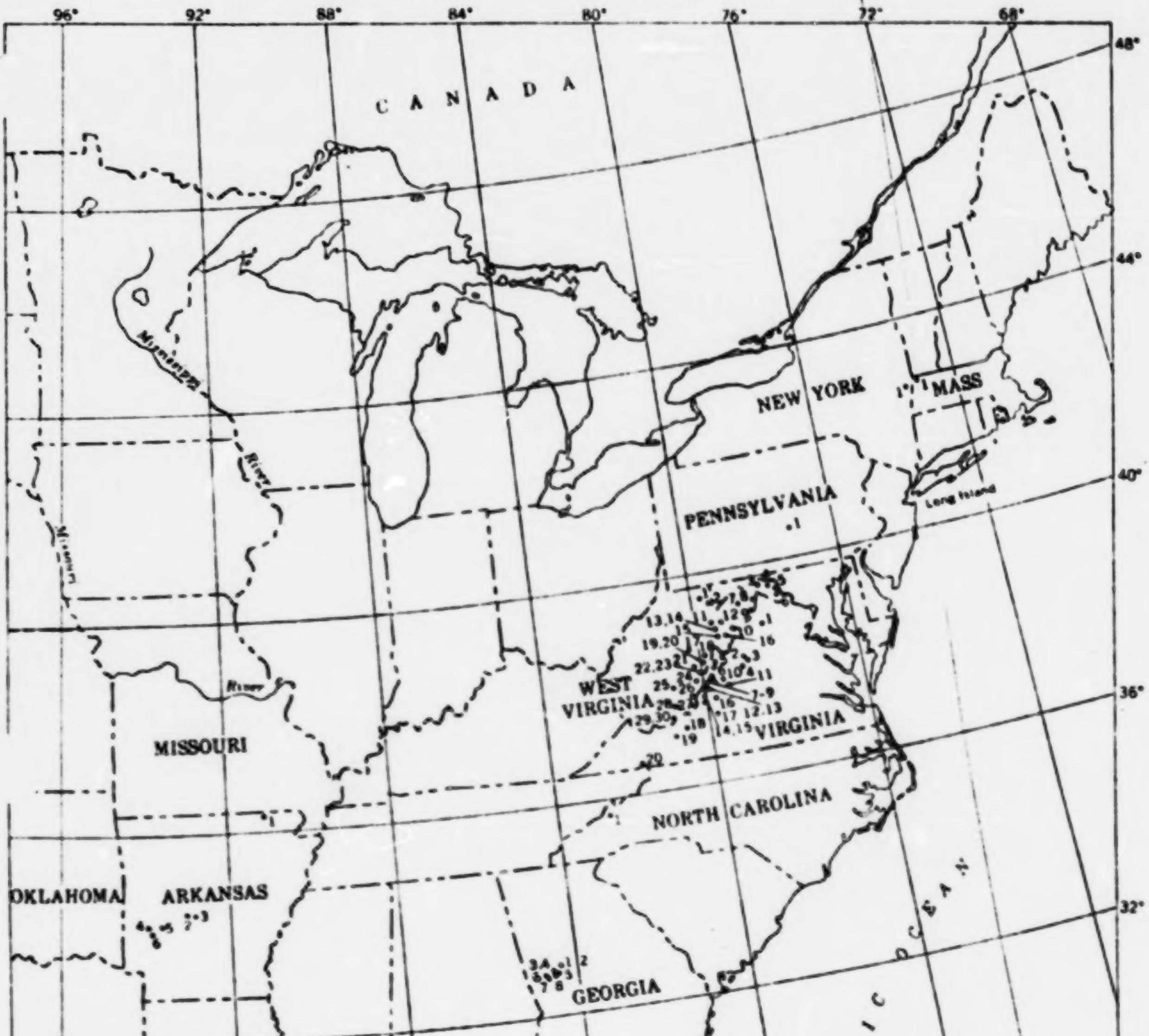
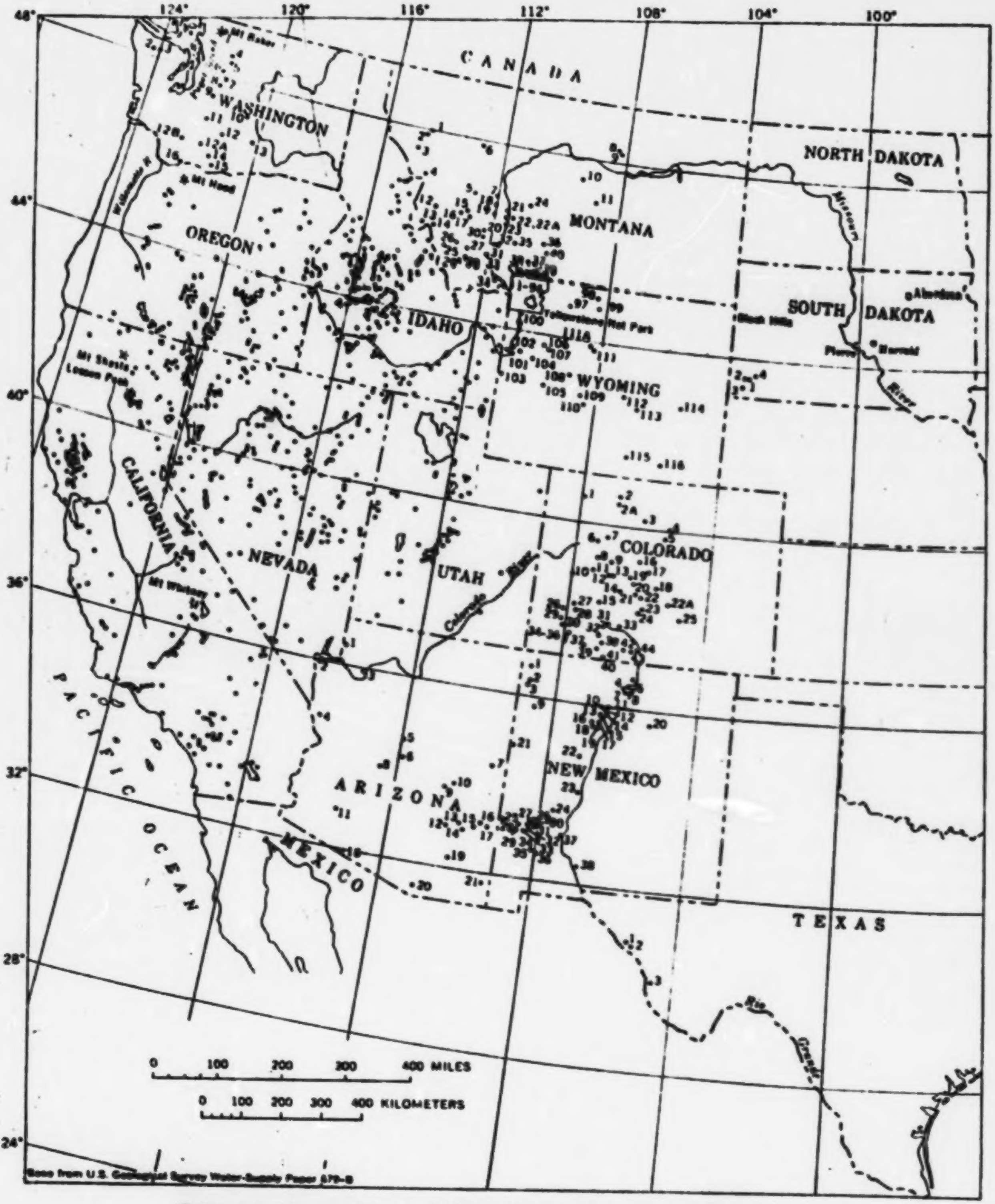

Hot spring or geyser
10° C at surface
Boiling begins
Rocks of low permeability
Hot water
Low density
Cold water
High density
Permeable rock
Crystalline rocks
Convecting (?) magma

Figure 3: Illustrations of a geothermal field showing how heat can be tapped. Adapted from Muffler, L.J.P., and White, D.E. (1972). The Science Teacher 39 (3), p. 40.


96°
92°
88°
84°
80°
76°
72°
68°
48°
44°
40°
36°
32°
28°
24°
C A N A D A
Mississippi River
Missouri
River
NEW YORK
MASS
Long Island
PENNSYLVANIA
WEST VIRGINIA
VIRGINIA
MISSOURI
NORTH CAROLINA
OKLAHOMA
ARKANSAS
GEORGIA
FLORIDA
A T L A N T I C   O C E A N
G U L F   O F   M E X I C O

Eastern part of the conterminous United States showing location of thermal springs.

Figure 4


124°
120°
116°
112°
108°
104°
100°
48°
44°
40°
36°
32°
28°
24°
CANADA
Mt Baker
WASHINGTON
Mt Hood
Willamette R
OREGON
IDAHO
MONTANA
NORTH DAKOTA
Missouri
SOUTH DAKOTA
Aberdeen
Pierre
Harrold
River
Black Hills
Yellowstone Nat Park
WYOMING
Mt Shasta
Lassen Peak
CALIFORNIA
NEVADA
UTAH
Colorado River
COLORADO
Mt Whitney
ARIZONA
NEW MEXICO
PACIFIC OCEAN
MEXICO
TEXAS
Rio Grande
0 100 200 300 400 MILES
0 100 200 300 400 KILOMETERS
Base from U.S. Geological Survey Water-Supply Paper 679-B

Western part of the conterminous United States showing location of thermal springs.

FIgure 5

THERMAL SPRINGS OF THE UNITED STATES AND OTHER COUNTRIES OF THE WORLD

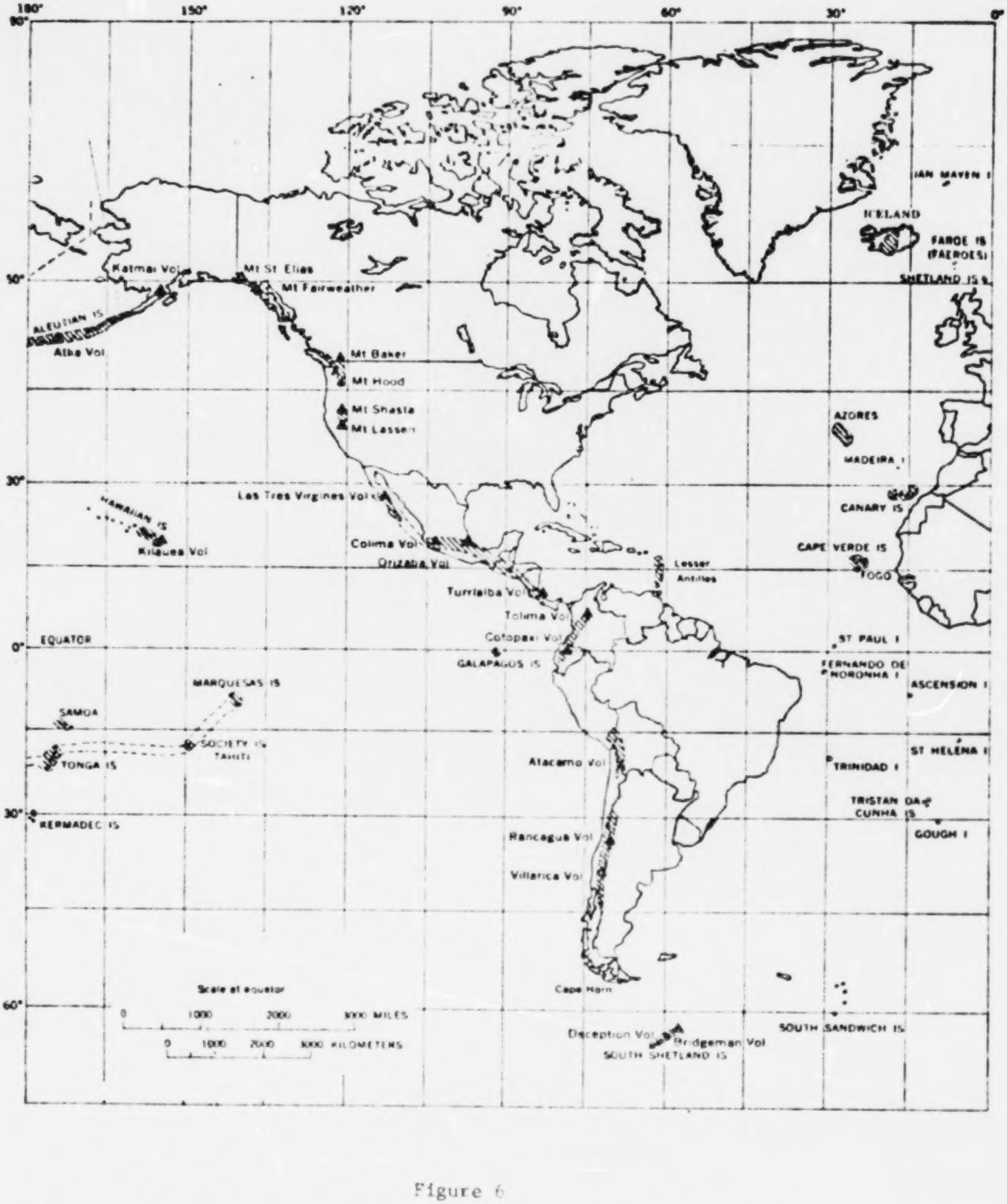

180°
150°
120°
90°
60°
30°
0°
90°
60°
30°
0°
30°
60°
JAN MAYEN I
ICELAND
FAROE IS
(FAEROES)
SHETLAND IS
Katmai Vol
Mt St Elias
Mt Fairweather
ALEUTIAN IS
Atka Vol
Mt Baker
Mt Hood
Mt Shasta
Mt Lassen
AZORES
MADEIRA I
CANARY IS
Las Tres Virgines Vol
HAWAIIAN IS
Kilauea Vol
Colima Vol
Orizaba Vol
CAPE VERDE IS
FOGO
Lesser
Antilles
Turrialba Vol
Tolima Vol
Cotopaxi Vol
EQUATOR
GALAPAGOS IS
ST PAUL I
FERNANDO DE
NORONHA I
ASCENSION I
MARQUESAS IS
SAMOA
SOCIETY IS
TAHITI
TONGA IS
Atacamo Vol
TRINIDAD I
ST HELENA I
TRISTAN DA
CUNHA IS
KERMADEC IS
GOUGH I
Rancagua Vol
Villarica Vol
Scale at equator
0
1000
2000
3000 MILES
0
1000
2000
3000 KILOMETERS
Cape Horn
SOUTH SANDWICH IS
Deception Vol
Bridgeman Vol
SOUTH SHETLAND IS

Figure 6

THERMAL SPRINGS

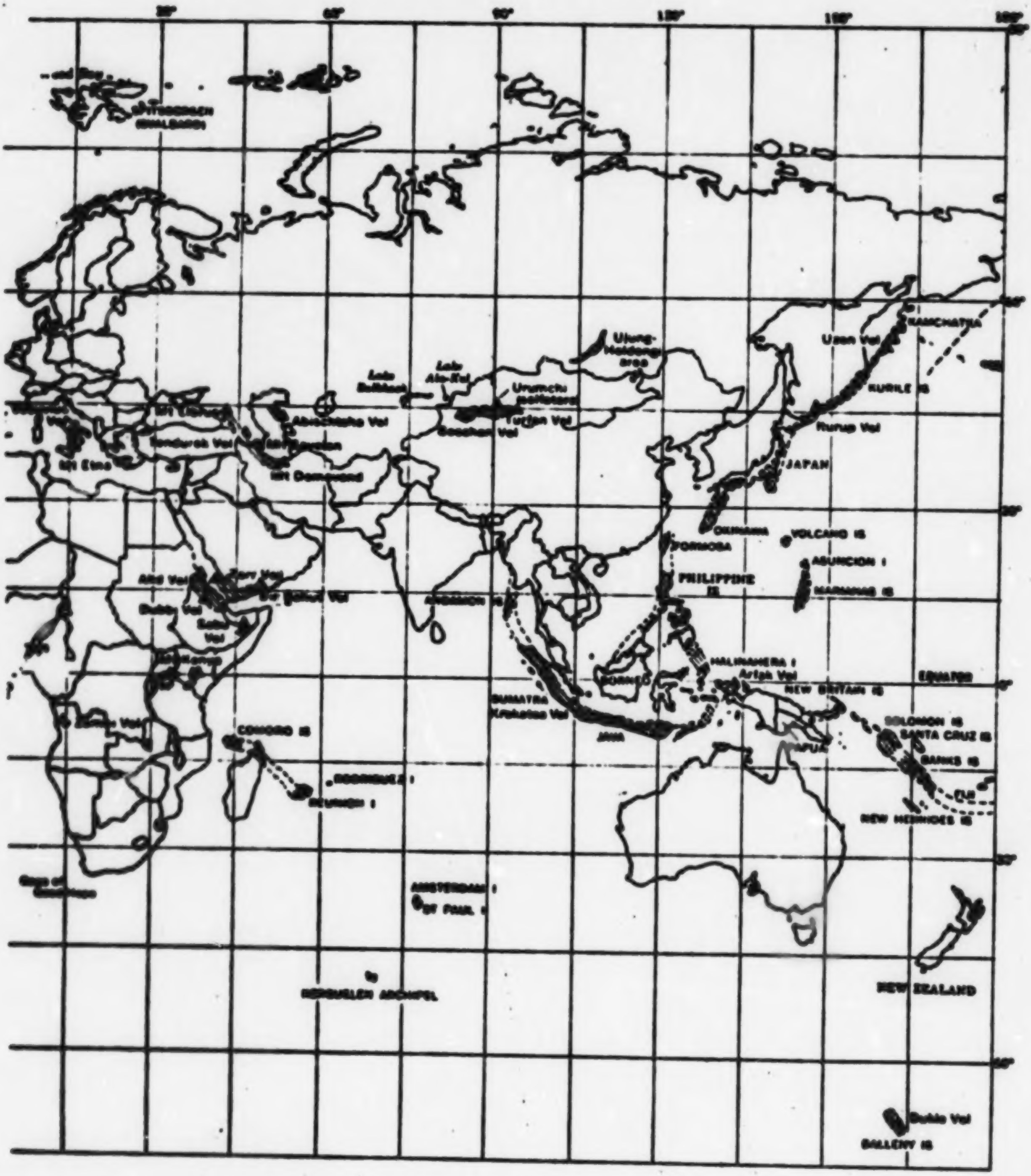
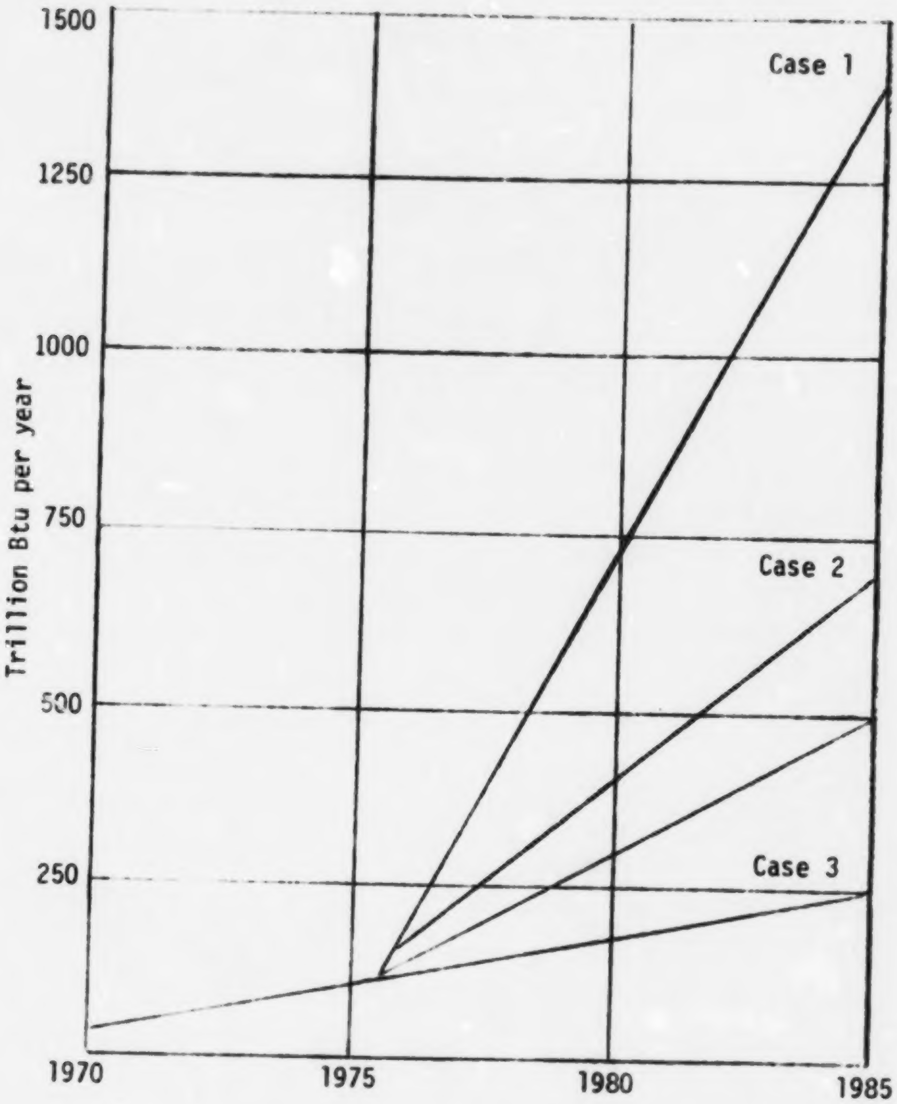

30°
60°
90°
120°
150°
180°
SPITSBERGEN (SVALBARD)
Lake Balkhash
Lake Ala-Kul
Ulung-Holdong area
Urumchi solfataras
Turfan Vol
Abochachs Vol
Mt Elbrus
Tondurek Vol
Mt Demavend
Mt Etna
Vol
Ala Vol
Dubbi Vol
Soka Vol
Vol
COMORO IS
REUNION I
RODRIGUEZ I
AMSTERDAM I
ST PAUL I
KERGUELEN ARCHIPEL
ANDAMAN IS
SUMATRA
Krakatoa Vol
JAVA
BORNEO
HALMAHERA I
Artah Vol
NEW BRITAIN IS
PAPUA
SOLOMON IS
SANTA CRUZ IS
BANKS IS
FIJI
NEW HEBRIDES IS
EQUATOR
NEW ZEALAND
Buckle Vol
BALLENY IS
KAMCHATKA
Uzon Vol
KURILE IS
Kurup Vol
JAPAN
OKINAWA
VOLCANO IS
FORMOSA
ASUNCION I
PHILIPPINE IS
MARIANAS IS

Figure 7



NOTE: In 1985, Case 1 represents 19,000 MWe of installed capacity; Case 2 - 9,000 MWe; Case 3 - 7,000 MWe Case 4 - 3,500 MWe.

Figure 8
TOTAL U.S. ENERGY FROM GEOTHERMAL SOURCES

SOURCE: National Petroleum Council

We should encourage the exploration for and exploitation of geothermal energy in localities where it is close to the surface and of sufficiently high heat quality. This would permit release of scarce conventional fuels for use in non-geothermal areas. The primary uses to date have been for the generation of electricity and for space heating.

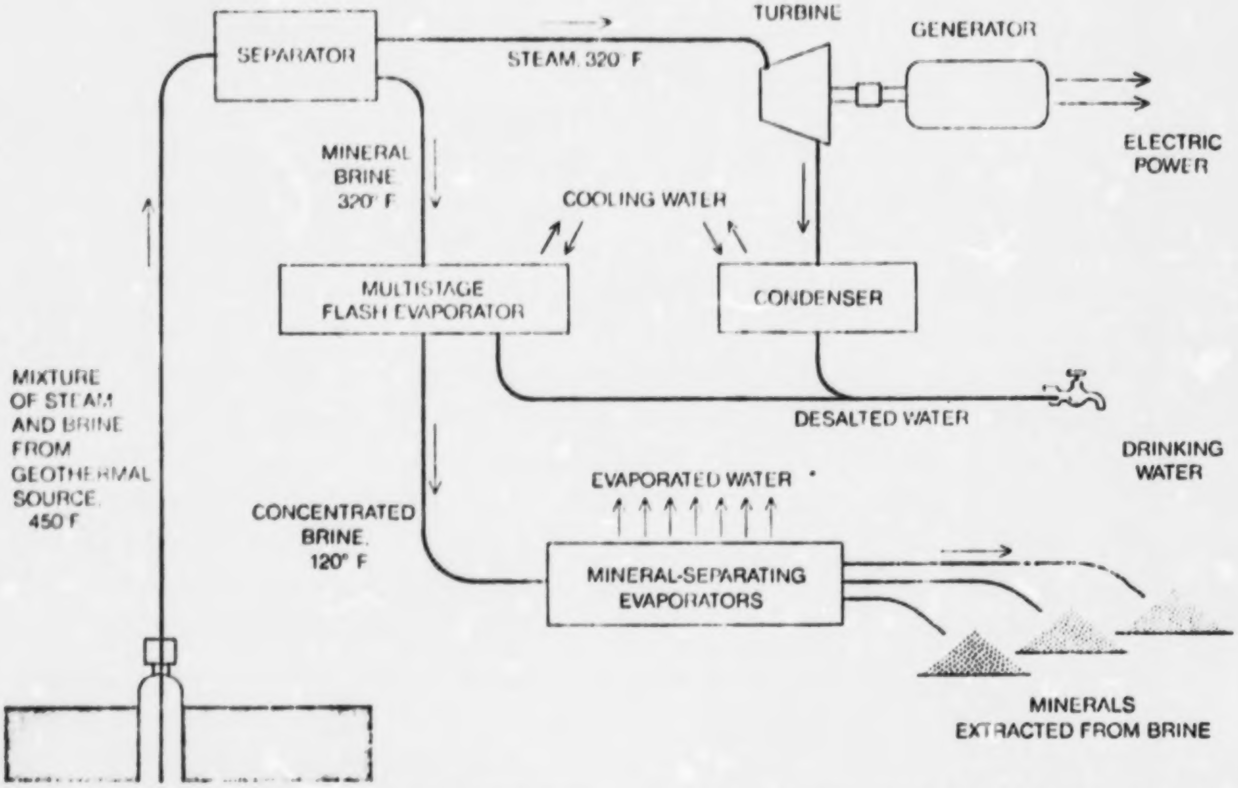
World-wide geothermal generating capacity (Figure 8) is about 900 MW, which is about 1/10 of 1 percent of world generating capacity from all modes. Most of this generating capacity is in three areas: Larderello in Italy, the Geysers in California, and Wairakei in New Zealand. There are also generating plants at Monte Amiata in Italy, Kawerau in New Zealand, Matsukawa and Otake in Japan, Pauzhetsky and Paratunka on the Kamchatka Peninsula in the USSR, Namafjall in Iceland, and Pathe in Mexico. Geothermal energy is used directly for space heating (Figure 9) in Iceland, the USSR, Hungary, New Zealand, and the United States.

There are several other, as yet minor uses (Figure 10), of geothermal heat. It is used in agriculture to heat greenhouses and soil. At Kawerau, New Zealand, geothermal heat is used in paper manufacture, and at Namafjall, Iceland for drying diatomite. At Rotorua in New Zealand, geothermal heat is used via a lithium bromide absorption unit to air condition hotels. Some geothermal fluids contain potentially valuable mineral by-products. Various schemes of desalination using geothermal heat have been proposed. And finally, there are the time-honored uses of geothermal waters for bathing and therapeutic purposes.

GEOTHERMAL RESERVES

A concept as superficially simple as geothermal reserves has considerable room for ambiguity and uncertainty. Furthermore, when we consider our inadequate knowledge of the nature and distribution of geothermal resources, we can see that there is reason for considerable disagreement on the magnitude of our geothermal energy reserves.

Potential annual production from geothermal sources under varying conditions as studied by the National Petroleum Council, ranges from 250 trillion Btu to 1.4 quadrillion Btu in 1985. Table I lists the types of resources; Figure 5 indicates three possible situations based on:


SEPARATOR
STEAM, 320° F
TURBINE
GENERATOR
ELECTRIC POWER
MINERAL BRINE 320° F
COOLING WATER
MULTISTAGE FLASH EVAPORATOR
CONDENSER
DESALTED WATER
DRINKING WATER
MIXTURE OF STEAM AND BRINE FROM GEOTHERMAL SOURCE, 450° F
EVAPORATED WATER
CONCENTRATED BRINE, 120° F
MINERAL-SEPARATING EVAPORATORS
MINERALS EXTRACTED FROM BRINE

MULTIPURPOSE DEVELOPMENT based on geothermal energy is being designed by the UN and the government of Chile for a geothermal field recently discovered in Chile. In this case the geothermal source produces a mixture of steam and mineral-rich brine. The steam and brine are separated, and the steam drives a turbine to produce electric power while the brine is put through an evaporator that concentrates it, thereby producing desalted water. The concentrated brine goes to a separator that extracts the minerals.

Figure 9*

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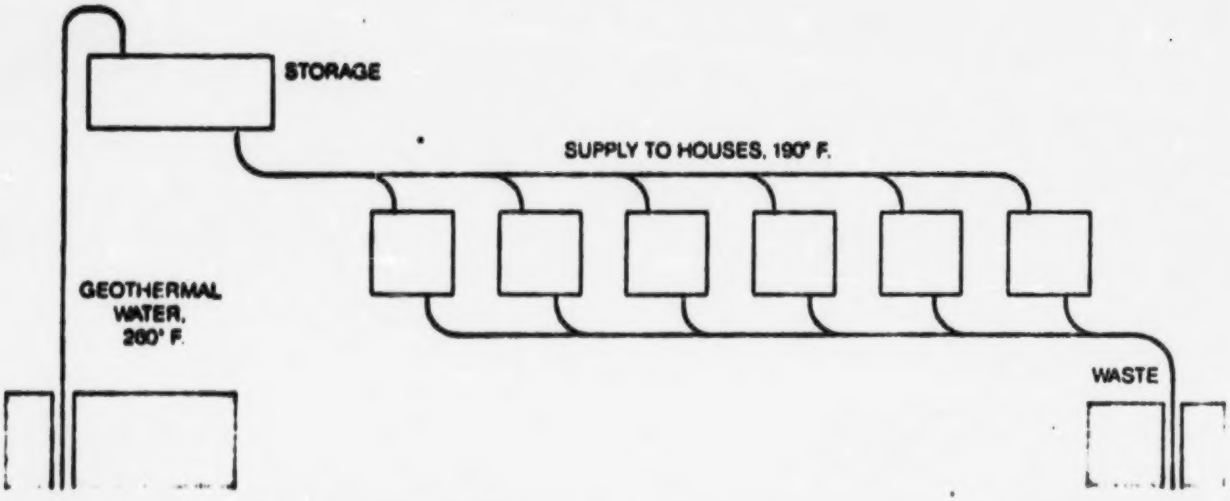
* from Barnea, Joseph, "Geothermal Power," Scientific American, Volume 226, Number 1, January, 1972, p. 77.


STORAGE
SUPPLY TO HOUSES, 190° F.
GEOTHERMAL WATER, 260° F.
WASTE

HEATING OF HOUSES and other buildings is done in a few places by a scheme such as the one shown here. Geothermal water is pumped to a storage tank, from which it flows to the buildings. Such systems are in use or being developed in several countries.

Figure 10*

* from Barnea, Joseph, "Geothermal Power," Scientific American, Volume 226, Volume 226, Number 1, January, 1972, p. 76.

Geothermal Target	Reserve Target for 1985	Resource Base
Localized hydrothermal systems, down to 2 mi. deep	5.6	560
Localized hydrothermal systems, down to 6 mi. deep	2.8	2,800
High-enthalpy waters, sedimentary basins	119	64,000
Magna chambers, within depths of a few miles	119	120,000-400,000
Low-enthalpy waters, sedimentary basins	635	640,000
Cratonic and platform areas, down to 6 mi.	2,000	20,000,000

*For comparison, heat of combustion of 1 bbl of oil is 5.8 million Btu. The recoverable amounts of heat are one to two orders of magnitude lower than the in-situ figures shown in this table.

TABLE I

IN-SITU HEAT RESOURCES

(quadrillion Btu)

Source: National Petroleum Council

(a) Large areas, including Federal lands available for prospecting
(b) A high success ratio in exploration and drilling (Case 1)
(c) Good success ratio (Case 2)
(d) Poor success ratio (Case 3)
(e) Availability of technology for hot water systems

A U.S. Geological Survey report[13] stated that over 1.83 million acres in ten Western states are within known geothermal areas, Table II. An additional 99 million acres are considered to have "prospective value" for geothermal steam. The USGS requirements for appreciable potential exploration are:

(a) Temperatures above 150° to 400° F, depending on use and processing technology;

(b) Under 10,000 feet depth for economic drilling;

(c) Rock permeability allowing heat transfer agent to flow at steady, high rate; and

(d) Sufficient water recharge.

ELECTRIC POWER GENERATION

There are two types of geothermal systems from which electricial energy is generated today. The first type is a vapor-dominated or "Dry Steam" system. Both steam and water are present at depth, with steam being volumetrically dominant in the hydraulically controlling phase. As water flows towards the well, it is vaporized. When the steam reaches the well head, it is superheated to become "dry" steam. The "dry" steam is piped directly into a turbine, where it drives an electric generator. Exhaust steam is condensed and the condensate discharged to the surface or reinjected into the ground. Examples of vapor dominated systems are the 356 MWe facility at Larderello, Italy and the 192 MWe combined generation capacity at the Geysers, California facility. At depth the temperatures in these reservoirs are 240° C (464° F) at pressures of about 530 lbs. per square inch. Unfortunately, these economically very favorable dry systems appear to be relatively rare.

Most geothermal systems appear to be of the hot-water type. The fluid at depth is a single phase - water - at temperatures well above surface boiling, owing to the hydrostatic pressure. Temperatures in hot water

TABLE II

KNOWN GEOTHERMAL RESOURCES AREAS

ALASKA
Pilgrim Springs
Geyser Spring Basin and
Okmok Caldera

CALIFORNIA
The Geysers
Salton Sea
Mono-Long Valley
Calistoga
Lake City
Wendel-Amedee
Coso Hot Springs
Lassen
Glass Mountain
Sespe Hot Springs
Heber
Brawley
Dunes
Glamis

IDAHO
Yellowstone
Frazier

MONTANA
Yellowstone

NEVADA
Beowawe
Fly Ranch
Leach Hot Springs

NEVADA (Cont.)
Steamboat Springs
Brady Hot Springs
Stillwater-Soda Lake
Darrough Hot Springs
Gerlach
Moana Springs
Double Hot Springs
Wabuska
Monte Neva
Elko Hot Springs

NEW MEXICO
Baca Location No.1

OREGON
Breitenbush Hot Springs
Crump Geyser
Vale Hot Springs
Mount Hood
Lakeview
Carey Hot Springs
Klamath Falls

UTAH
Crater Springs
Roosevelt

WASHINGTON
Mount St. Helens

reservoirs have been measured as high as 380° C (716° F) at Cerro Prieto in Baja, California. As the water passes up the well, it partly flashes to steam. Steam and water are separated at the surface, with only the steam passing through to the turbine generator. The major hot water system producing electricity today is Wairakei, New Zealand at 160MW capacity. Cerro Prieto at 75 MWe is scheduled to go on line this year.

When one looks at geothermal reserve figures, one must ask whether a given reserve figure represents heat in the ground, heat at the well head, heat at the turbine intake, or electricity generated. By no means can one get all the heat out of the ground. There will be in each field a temperature below which heat extraction becomes uneconomic. Furthermore, not all the heat above this temperature can be extracted, owing to local impermeability and non-optimum well spacing. Second, in a hot water system, for example Wairakei, half the heat brought up the well is in the water phase and cannot be run through the turbine. And thirdly, because of the relatively low pressures and temperatures of geothermal steam, electric power Plant efficiencies are about 15%, considerably lower than modern fossil fuel or nuclear plants.

Present day geothermal plants that use steam directly (single fluid conversion) in the turbine require a reservoir temperature of at least 180°C. At lower temperatures, the steam flashed is quantitatively insufficient. There are several technological breakthroughs that are being actively pursued today.

The first involves a potential method for generating electricity from a low-temperature hot-water system. The proposed system doesn't involve flashing and theoretically can use waters down to 100° C and lower. Water is pumped to the surface under pressure so that it does not vaporize, and its heat is exchanged with a low-boiling point fluid such as iso-butane. The iso-butane vapor drives a turbine, is condensed and recirculated in a continuous loop. A variant of this scheme is to be tested this year by San Diego Gas and Electric in the Imperial Valley of California. The Russians have a similar pilot plant using "Freon" at Paratunka in Kamchatka, where the intake water is only 90° C. The results are not known.

Another technological breakthrough may lie in the exploitation of what are called hot dry rock systems; that is, geothermal systems that are hot but lack natural permeability and naturally circulating fluids. There are two groups of investigators that are attempting to develop such systems. One group, involving Battelle Northwest, Roger Engineering, and Southern Methodist University, plans to put a deep drill hole at the heat flow anomaly discovered at Marysville, Montana. Another group, at Los Alamos Scientific Laboratories in New Mexico, is investigating an area of high heat flow just west of the Valles Caldera.

The basic idea is to drill a hole to a depth of about 4 km. and to fracture the earth about the end of the hole, up to 4 km. in radius. A second hold is drilled to intersect this region. Then cold water is pumped down the first hole, is heated, and rises to the surface with a temperature of 250° C and 80 kg/cm^2, where it flashes to steam.

Fracturing of the hot rock at depth can be accomplished with cold water, dynamite or nuclear devices.

In July, 1974, a U.S. interagency task force reported that geothermal electric-power generating plants could be producing 30,000 megawatts by 1985 and 100,000 megawatts by 1990. This task force recommended that the National Geothermal Energy Research Program of the National Science Foundation be "accelerated on an orderly basis" so that a million barrels a day of oil could be saved by 1990 and 3-6 million barrels per day by the year 2000.

LAND USE (The Geysers)

Table III gives estimates of land needed to support a 1000 megawatt plant. Surprisingly, coal and geothermal developments occupy about the same areas. However, the coal plant is essentially a strip mine. The geothermal plant represents far less intensive use. At Larderello, Italy, it is possible to grow grapes among the geothermal fields to take advantage of the increased moisture content of the air. Cattle grazing is being experimented with at The Geysers. The question of desirability of significant human habitation close by is more difficult to deal with. It is also clear that if land use is the prime consideration, then the nuclear power plant deserves high marks.

TABLE III

LAND USE ESTIMATES

1000 Megawatts of electrical output 30 year estimated lift time in square miles

	Fuel Recovery	Power Plant
Coal[1]	10 - 40	3/4
Geothermal[2]	10 - 15	Included
Nuclear[3]	1/4 - 1/2	1/2

[1] Four Corners Plant, New Mexico, Coal Strip Mine

[2] The Geysers, verbal estimates from Union Oil Company based on vapor type source.

[3] Converse Uranium Mine, Environmental Impact Statement, Wyoming Proposed Mendocino Power Plant site (two units totalling 2260 megawatts on one site)

The above estimates of necessary land imply decisions about well spacing and allowances for possible additional drilling to sustain production for 30 years. These are based on company classified information of which we have no knowledge.

LIFE TIME OF THE FIELDS

Most of the knowledge in this area is company classified; however, we do know that the fields at Larderello, Italy, have been in operation for nearly 70 years. Perhaps one really finds out by trying. It is important to realize that a vapor dominated system gives little warning of impending depletion. There is more heat than water and the steam pressure remains high until the very end.

It may be possible to inject more water to rejuvenate the field. Right now only about 20% of the condensed steam is reinjected. The rest is evaporated to cool the outlet of the turbines to improve the thermodynamic efficiency.

LAND SUBSIDENCE AND EARTHQUAKES

These are not big problems around the Geysers. The pressure remains constant until the field is depleted and the rocks are not subject to new stresses until then. In a hot water system, removing water has caused land subsidence (Wairakei in New Zealand). There have been noticeable increases in microearthquakes around The Geysers and the meaning of this is not clear.

COOLING PROBLEMS

Nature provides the geothermal steam at 179° C compared with about 500° C steam used in fossil fuel plants. Thus, the thermodynamic efficiency of the geothermal plant is less - 15% being typical. To achieve even this efficiency it is necessary to cool the exhaust of the turbines to reduce the back pressure to almost a vacuum. This requires cooling towers. Fortunately, there is enough water from the steam to supply the towers. The potential for atmospheric modification is present and has not been studied in detail; however, the plants are distributed over a large area and locating the cooling towers in places where there are stronger winds should aid in the dispersion of the heated air.

POTENTIAL AIR QUALITY DEGRADATION

The sulfur as H_2S is perhaps the most significant problem health-wise and this is reflected in very stringent air quality standards. Table IV reveals that the Geyser's geothermal steam is worse than an oil-gas fired plant. The Geyser output is nearly pure steam with only 0.55% H_2S. Unfortunately, the thermodynamics are poor and we must use 18.2 lbs. of steam to produce a kilowatt hour, or about 0.1 lb. of sulfur per kilowatt hour.

At an oil fired plant, approximately 0.5 - 0.6 lbs. of oil will do the same job. Thus, the geothermal steam is equivalent to 1.8 - 2.3% sulfur content oil - Table IV. This is high sulfur fuel by present standards.

The potential for solving this problem is somewhat better than at a coal or oil fired plant. First, the non-condensable gases are already collected separately. Thus they can be dealt with. The portion of the gas evaporating from the cooling towers is harder to deal with, though. Secondly, the reinjection well provides a ready disposal site, back into the earth. Reinjection was initially begun to prevent the slight amount of boron from contaminating the surface waters. At present time there appears little risk of substantial surface water contamination.

EARLY ESTIMATES

The residence time of the sulfur compounds in the air was considered to be less than a week (The Sulfur Cycle, Science, 175, 587 (1972)). Recent studies indicate that the time is proportional to many factors and is being reviewed and studied. Thus, while the problem is serious and must be dealt with, one should maintain some perspective. The problem most directly affects people living near the geothermal areas and these areas, to date, are not thickly settled.

NOISE

Measurements of noise levels as they existed at The Geysers on March 11, 1973 are given in Table V. Conclusions depend very much on the reference frame of the observer. They are not much above those found in relatively quiet residential neighborhoods. It would seem that the noise of routine

TABLE IV

COMPARATIVE WASTE PRODUCTS

In tons per day for 1000 Megawatts electrical output

Substance	Oil & Gas Plant[1]	Geysers[2]	Nuclear[3]
H_2O	8,400	217,000	---
CO_2	16,400	1,700	---
Organics	.23	260	---
Sulfur Compounds	1.7	110	---
Nitrogen Oxides	19.2	---	---
Radioactive Wastes	---	---	0.26

[1] Data are for PG&E Pittsburg Plant (1971) taken from Air Pollution and the San Francisco Bay Area, Seventh Edition, Bay Area Air Pollution Con- District, San Francisco, CA, 1972. This plant burned a combination of oil and natural gas during the period reported on.

[2] Data of geothermal steam composition are from Finney, J.P., The Geysers Geothermal Power Plant. Chem. Engineering News 68, 83 (1972). The organics are methane and ammonia. THe sulfur is as hydrogen sulfide.

[3] Data from Preliminary Safety Analysis and Environmental Impact Statement for PG & E proposed nuclear power plant: Mendocino Units 1 and 2. Tonnage is for total of shipments from the site averaged over a year and scaled to 1000 megawatts. Breakdown: 0.07 tons of spent fuel and 0.19 tons of packaged wastes.

TABLE V

NOISE LEVELS AROUND THE GEYSERS

Measurements on 3 - 11 - 73

Location of Measurement:	Level in decibels "A" weighting
Outside Units 5 & 6 - inside protective fence	73
Geyser Resort approximately .5 mile from field	63
1.5 miles across valley	53

For comparison the following are offered:

Valley not associated with geysers approximately 7 miles distant	43
Near Stream in above valley	63
Berkeley, east side of campus, evening of 3-2-73	60
Vallejo, residential area, early evening of 3-2-73	58
Home, 5850 Henning Road[10] Sebastopol, evening of 3-11-73	43

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[10] Dunning, Sonoma State College, Sonoma California, private conversation.

power generation can be reduced to almost arbitrarily low levels.

LONG RANGE QUESTIONS

These are largely concerned with effects too subtle to show up now, because of the small scale of activities or the long time scale over which they act. Among them are field life time, earthquake possibilities, subtle effects on the water in tables, and possible meteorological effects. Many of these questions will be best resolved by careful monitoring of the effects in question while continuing geothermal development. Constraints, as suggested by the NPC, are listed in Table VI.

Geothermal Target	Current Constraints	Subsequent Constraints	Outer Contingency
Localized hydrothermal systems down to 2 mi. deep	Leasing, exploration, economics	Small resource base	Air and water pollution
Localized hydrothermal systems down to 6 mi. deep	Economics	Leasing, exploration	Air and water pollution
High-enthalpy water, sedimentary basins	Exploration, deep drilling	Economics	Brine disposal and utilization
Magma chambers within a depth of a few miles	Exploration, R&D Magmas	Economics	Unknown
Low-enthalpy waters, sedimentary basins	R&D power generation	Exploration, economics	
Cratonic and platform areas, down to 6 mi.	R&D Plowshare	Economics	Radioactive pollution

Source: National Petroleum Council

TABLE VI

CONSTRAINTS TO GEOTHERMAL RESOURCE DEVELOPMENT

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5-1

James W. Meyer
December 1, 1974

Monograph No. 5
MIT Energy Laboratory
HYDROELECTRIC POWER

In mid-1974 the total conventional hydroelectric power developed in the contiguous United States averaged 260 billion kilowatt-hours annually from a capacity of 55,000 megawatts. Nearly one-half of this capacity and more than one-half of the generation is in the pacific states, Washington, Oregon and California.

Nearly 7,000 megawatts of capacity are now under development, 90% of which is in the pacific states.

A review of potential sites for hydroelectric developments with capacities of 100 megawatts or more, or additions of 25 megawatts or more found 44 new sites and 26 potential additions that might be completed through 1933. Of this total of 70 sites, only one is in New England: Dickey-Lincoln School. The expected installed capacity of Dickey-Lincoln School would be 830 megawatts with an average annual generation of just over one million megawatt hours. Friends of the St. John aver that "The Dickey-Lincoln Project will never solve the energy crisis because the project is not big enough. Nor can it be made bigger or be operated for a longer period daily, because the water supply is too limited for large or larger operation. New units, such as Boston Edison's Mystic No. 7 or Pilgrim No. 1, each produce about four times as much as Dickey-Lincoln would. Thus, the dams cannot take the place of new nuclear or fossil-fueled power plants."

Forty existing hydro facilities could be expanded to add 12,700 megawatts of capacity. Most of these facilities use all of the available water now so that expanding capacity could only be done at the cost of reduced operating time.

The number of favorable sites available for conventional development is limited. There are pros and cons for the development of the remaining potential such as the production of power without consuming fuel versus the replacement of flowing streams with reservoirs and changing the character of a scenic valley. It might be mentioned that because of their ability to pick up load and change the rate of output quickly, hydroelectric plants are particularly suited for providing peak and reserve capacity for utility systems.

Pumped storage is closely related to hydro power in that a reservoir at a height to provide a head is kept full using excess capacity from fossil fueled or nuclear plants during off peak periods so that hydrogeneration from this storage could be used to meet peak load demands.

Pumped storage also presents controversial issues. Consolidated Edison Company of New York has been involved in a decade of proceedings and litigation over its proposed 2000 megawatt hydroelectric facility in the Hudson River highlands, the (Storm King) "Cornwall Project."

As of May 1974, the total developed pumped storage capacity in the contiguous United States amounts to a little over 8,000 megawatts.

There is only one sizeable tidal power project in the world -- the 240-megawatt Rance project in France. Passamaquoddy Bay is the most favorable site in the United States and Canada. Studies of the project in the 1960s indicated that the contemplated 500 megawatt plant was not economically justified. Even if increasing costs of power from alternative sources and improvements in the techniques of construction result in economic feasibility, substantial environmental issues would have to be resolved such as the flooding of valleys, the relocation of populations and wildlife, alteration of ground water tables and changes to drainage patterns of stream and river flows. Tidal projects effect shipping, fishing, and coastal ecology and pumped storage has the problem of a widely varying waterline with the ebb and flow of electric power demand. Detractors claim that it lessens the pumped storage pond's value as a recreational site, and at low water is an eyesore.

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James W. Meyer
December 1, 1974

Monograph No. 6

MIT Energy Laboratories

OIL SHALE

For years the hundreds of billions of barrels of oil equivalent locked in several basins of the Rocky Mountain's Green River Formation in the tri-state area of Utah, Wyoming, and Colorado has looked like an unexploited (perhaps unexploitable) bonanza of fossil fuel. Oil shale is neither oil nor shale, strictly speaking, the "oil" being an organic polymer called kerogen, the "shale" a marlstone-type inorganic component. Cowboys used to burn oil shale in their campfires and some hapless early settlers of the region attempted, with disastrous results, to build fireplaces with the attractive grey-tan stone.

In the Piceance Creek Basin, Colorado, there are an estimated 160-billion barrels of shale reserves near the surface; of which 34-billion barrels are considered recoverable.

Most processes for recovering oil from oil shale involve heating to decompose the kerogen to volatile oil and gas followed by condensation and recovery of the vapors. Most oil shale in the western formations contain at least 25 barrels of oil per ton of shale.

The three major components of shale oil production are mining, crushing, and retorting. The Oil Shale Corporation (TOSCO) has operated a 1,000-ton per day semiworks plant near Grand Valley, Colorado, to develop the TOSCO II process. Commercial design is now underway. Yields of the TOSCO II process with shale from the Piceance Basin were 33 gallons per ton of shale. Shale oil differs from petroleum in that it contains a higher proportion of nitrogen and oxygen.

The U.S. Bureau of Mines' Laramie, Wyoming Research Center has experimented with _in situ_ extraction of oil from shale. In the experiment shale was fractured with nitroglycerin, ignited and allowed to burn six weeks, resulting in recovery of 190 barrels of shale oil. Gerald Dinneen, Director of Research, believes oil shale retorting and _in situ_ extraction may be the most economical. Experiments thus far have been on far too small a scale to permit meaningful extrapolation of economic factors to large scale commercial production.

Garrett Research and Development Co., research arm of Occidental Petroleum Corporation, has reported a test project for in situ recovery of shale oil on a 4,000-acre tract on the southern edge of the Piceance Basin. The process involves some mining, large-scale rock breakage, and retorting in place. Total recovery of oil has not been disclosed but consistent pumping of 25-30 barrels per day has been mentioned. The pilot plant is on a very small scale but the Garrett firm believes commercial scale is feasible within 3 years with intensive development effort. The problems of expanding the scale of the plant have to be fully explored and when they are uncovered and solved, 3 years is likely to be quite optimistic if a 40,000 barrels per day plant is to become operational. The technique does have promise of producing shale oil at lower cost than mining and surface processing, and it does require less water. It is the only one of several in situ techniques for which much success has been claimed.

Morton M. Winston, President, TOSCO expects the completion of the first commercial oil shale complex in the spring of next year. The plant will produce 46,000 barrels per day of refined products (equivalent to 51,000 barrels of crude). Winston estimated that 600-billion barrels of shale oil were recoverable from the Green River Formation. He also stated that first generation commercial plant complexes can be commenced as early as 1979.

Fred L. Hartley, Union Oil Company, has reported a process that will recover 82% of the thermal energy in the shale in the form of syncrude or high BTU gas. The three main problems facing oil shale development are:

1. Political
2. Financial
3. Water

Water availability could limit shale oil production to 1-2-million barrels per day.

Hartley reported estimated costs for a 100,000 barrel per day shale oil complex for the years, 1970, 1974, and 1980, and the per barrel price of oil based on a 15% return on investment:

1970	$ 525-million	$ 5.00/bbl
1974	$ 790-million	$ 7.00/bbl
1980	$1400-million	$11.50/bbl

In face of such huge investments to produce a product equivalent to that produced elsewhere in the world for as little as 25¢ - 75¢ per barrel, there is increasing scepticism about the viability of extensive production of oil from shale. This scepticism is expressed even by those companies that have spent hundreds of millions of dollars for their leases. Moreover, Montana Governor Thomas L. Judge warns that land and water supplies cannot support both an expanded agricultural economy *and* a full-scale energy development. According to an environmental impact statement published by the Department of the Interior in August, 1973, a 1-million-barrel-a-day operation would require between 107,000 and 170,000 acre feet of water a year, and municipal development associated with industrialization of the area would require another 14,000 - 19,000 acre feet of water. The impact statement suggests that about 340,000 acre feet of water is potentially available for oil shale operations. The chief consumers of water in oil shale production are spent shale disposal and shale oil upgrading so that it can be transported by pipeline.

The above water problems make *in situ* processing appear attractive; however, one indication of the fact that most of the oil industry is not willing to venture into this unknown area is that of the six tracts of land put up for lease by the Federal government, the two that were suitable for *in situ* methods failed even to attract a single bid.

An AEC study recommended that the Federal government assist industry to establish a plant capable of producing 30,000 to 50,000 barrels of oil a day to demonstrate the technology of *in situ* processing on a commercial scale. If construction were to begin in 1975, the demonstration plant would be in operation in 1977, and if proven successful, an industry production capability of about 1.8 million barrels per day could be achieved by 1985.

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James W. Meyer
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Amended June, 1975
William J. Jones

Monograph No. 7

MIT Energy Laboratory

SOLID WASTE FOR THE GENERATION OF ELECTRIC POWER

Solid waste is an ubiquitous, self-renewing energy source concentrated in our population centers. Americans produce between 200 and 300 million tons of solid waste a year, around a ton for every man, woman and child in the country, enough to cover the entire state of New Hampshire with a layer six inches deep. Estimated on the basis of population, New Hampshire accounts for 700,000 tons/year. We dispose of 90% of our waste in land fills, 8% in incinerators, and 2% by other means. Urban solid waste consists typically of 40-45% paper, 20-25% organic materials, and the remainder, 30-40% metals and glass. Such solid waste has an energy content of from 4,500 to 5,500 Btus per pound.

Most major metropolitan areas are running out of places to put it all. New York City for example, expects to overflow its available dumping grounds in the next several years. More than twenty cities are looking for other solutions.

The Union Electric Company in St. Louis has been processing and firing a mix of solid waste with coal to produce 125 MWe electricity. The proportion of solid waste is 15-20% of the heating value of coal or 400 to 600 tons per day. The heating value of coal averages 11,500 Btu/lb, the heating value of the waste 4,600 Btu/lb. This experimental prototype has been in operation since mid-1972. A new $70-million plant is being built which will generate about 6% of its power from solid waste and will draw trash from St. Louis and six adjoining Missouri and Illinois counties. The project is scheduled to be in operation by mid-1977 and could save Union Electric up to $10-million a year in fuel costs. Annual operating costs of the facility are expected to be $11-million.

Garrett Research and Development Company, La Verne, California has developed a solid waste pyrolysis process which produces from each ton of refuse almost 1 barrel of oil, 140 pounds of ferrous metals, 120 pounds of glass, 160 pounds of char, and varying amounts of medium energy gas (400 to 500 Btu per scf). A 200-ton-a-day demonstration plant handles all the solid wastes produced by Escondido and San Marcos, California. Oil from the plant will be sold to the San Diego Gas and Electric Company. Garrett estimated in 1972 that a full-scale, 200-ton-per-day plant to process wastes from a city of 500,000 would cost about $12-million.

Monsanto Enviro-Chem Systems, St. Louis, Missouri, has operated a 35-ton-per-day pyrolysis plant which served as a prototype for a 1000-tons-per-day plant for the City of Baltimore (population 900,000). Two waste heat boilers will produce steam for Baltimore Gas and Electric Company; 200,000 pounds per hour of steam for each 1000 ton-per-day boiler. The project cost is just under $15-million and anticipated operating costs are roughly $6-per-ton.

The Nashville Thermal Transfer Corporation, Nashville, Tennessee (population 500,000) is operating a district heating and cooling system on solid waste. Two units, each able to handle 860 tons-per-day are being installed in the $16.5-million total system which includes distribution. Presently 200-tons-per-day are being burned to produce 200,000 pounds of steam per hour. Both steam and chilled water are distributed in a four-pipe system.

The City of Seattle (population over 500,000) has made an exhaustive study of the disposal and/or utilization of 550,000 tons-per-year of solid waste. As a result of the study, a recommendation was made that Seattle's solid waste be converted to methanol at an estimated rate of about 40-million gallons a year. It was suggested that methanol would be an ideal fuel for a gas turbine powered electrical plant. Methanol is also a good fuel for use in fuel cells.

Columbia University workers have studied the problem of the economic utilization of municipal refuse for the City of New York in a National Science Foundation (RANN) sponsored program. It was concluded that, for New York City, the Union Carbide Oxygen Refuse Converter would be the best choice. The Union Carbide Corporation is currently proceeding with plans to erect a 200-ton-per-day demonstration in Charleston, West Virginia to be operated with mixed municipal refuse supplied by that municipality. The disposal of de-watered sewage sludge by pyrolysis can also be evaluated.

Parson and Whittemore Inc. is to build a $44.6-million, 2000-tons-per-day recycling plant for Hempstead, L.I., a city of 800,000 people. Long Island Lighting Company will buy combustibles to produce 225 megawatts of electricity.

Characteristics of these planned and operating facilities is that they are designed for populations of 500,000 or more in a reasonably compact area. This facilitates the collection and eases the transportation costs of solid waste. Energy costs of collection and transporation rise quickly for dispersed populations. Many of these urban centers have populations equal to or greater than the entire State of New Hampshire.

If we base our estimates on population, the Cities of Portsmouth and Dover produce about 50,000 tons of solid waste a year. About 10,000 BTUs are required to produce a kilowatthour of electric energy in a conventional steam plant. If the solid waste used has an average energy content of 5,000 BTUs per pound or 10-million BTUs per ton, one megawatt hour of electric energy can be produced from each ton of solid waste. If it were possible to collect, transport and produce all the solid waste from Portsmouth and Dover, for example, we could produce 50,000 megawatt hours per year. It would be necessary that the plant operate all of the time and it would be possible to store and use waste independently of day-to-day variations in amount and kinds of waste.

A 1200 megawatt electric generating plant, operating only half the time, produces over 5 million megawatt hours a year. To produce an equivalent amount of electric energy from solid waste, we would have to derive it from an aggregate population of 5 million people---about the population of the State of Massachusetts. From a consideration of energy, these conversion methods are severely restricted by the limited amount of solid wastes available and transportation costs and problems from over the entire region to the central bulk generating plant.

For urban regions and smaller sized urban centers, waste must be considered more as sources of supplementary fuels than alternative total resources.

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James W. Meyer
December 1, 1974

Monograph No. 8

MIT Energy Laboratory

ENERGY FROM FORESTS AND PLANTATIONS, AND OTHER BIOMASS

The first source of "artificial" energy was wood. It furnished heat and light and, indirectly, power. Trees, bushes, straw and farm by-products still provide fuel in a sizeable portion of the world. Its use is mostly limited to single family units.

Wood as a Fuel for Electric Power

Much to the surprise of many people, New England has increasing numbers of acres of its land area in forests. A century ago, Massachusetts was two-thirds cleared and one-third forest -- today the reverse is true. Seedlings quickly spring up in abandoned clearings which in time become dense second growth timber stands. The Forest Resource Report Number 20, October 1973 gave the following figures for wooded land in the states of New England:

	Acres of Land Area (in thousands)	Forested Area (in thousands)
Maine	19,797	17,748
New Hampshire	5,781	5,131
Vermont	5,935	4,391
Massachusetts	5,013	3,520
Rhode Island	671	433
Connecticut	3,116	2,186

Source: U.S. Department of Agriculture, Forest Service, Forest Resource Report Number 20, October 1973.

The Forest Survey Project of the Northeastern Forest Experiment Station of the U.S.D.A. Forest Service has estimated the volume of hardwoods grown each year that is not used for other forest products which could be consumed in each state as firewood without depleting the forests, that is, growth and harvesting would be equal. These estimates are shown in the following table:

	Estimated cords of hardwood available for fuelwood (in thousands)	Tons (in thousands)
Maine	338	845
New Hampshire	727	1,817
Vermont	215	537
Massachusetts	409	1,022
Rhode Island	65	162
Connecticut	442	1,105

If weed trees, culls and tops and limbs of trees harvested for other purposes are included, the estimate about doubles for each state. The heat value of wood varies from about 27 million Btu/cord for the best dry hardwood to a little over 10 million Btu/cord for the poorer green wood. Thus the best wood has a heat value equivalent per cord to just under 200 gallons of fuel oil. If all the available fuelwood in New Hampshire were to be used under boilers for generating electric power, about 15 trillion Btu/year would be produced (assuming 20 million Btu/cord). Further assuming a heat rate for the power generating plant of 10 Btu/kWh, 1.5 million megawatt-hours per year would be produced. This is equivalent to a 200 megawatt station operated year round. Clearly the task of cutting, chipping and transporting this much woodfuel from all over the state of New Hampshire would be a prodigious task.

Forests are like any other agricultural product. The soil must furnish nutrients in order for the trees to grow. In an undisturbed forest, leaves and dead trees remain on the ground and by their decay return the nutrients to the soil. Forest harvesting will require that the nutrients, lost by removal of the wood to a generating plant, would have to be made up by commercial fertilizers, which currently require petrochemicals.

Szego and Hemp(1) have made an extensive study of the potential for energy forests and fuel plantations and estimated that 400 megawatts of electric power could be continuously supplied from a land area of 400 square miles managed and harvested in a manner similar to southern pulp mill plantations. In their 1973 paper, they estimated the capital costs for the plantation and power station at about $400/kW. A portion is attached as Appendix I. Sidney Katell, referee of Szego and Kemp's paper independently estimated the cost of southern pine wood fuel as being equivalent to $25 per ton coal. He based this estimate on the following assumptions for a forest in a southern state (e.g. Georgia):

1. Production: 5 tons per acre-year
2. Land cost: $50 per acre
3. Harvesting cost: $9 per ton
4. Interest plus taxes: 8.6% of land cost.

These assumptions are admittedly optimistic.

The Green Mountain Power Corporation of Burlington, Vermont is considering the establishment of a small 4000 kilowatt wood-burning electric generating facility as a pilot project to test the feasibility of procuring wood chips as a fuel. Satisfactory results could lead to the construction of a larger wood-fired generation facility. The following sets forth the basic assumptions[1] concerning wood supply, costs, and other procurement considerations which led to the initiation of this feasibility investigation.

Vermont is 73 percent forested. At its current rate of growth, there is an annual growth surplus after harvests of 1.8 million tons of wood. It takes about 7.5 tons of wood each year to fuel a one-kilowatt electric generating plant. There should be, therefore, adequate annual surplus growth to fuel a plant one-half as large as the Vermont Yankee nuclear powered 550 megawatt electricity generating plant.

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[1] Beardsley, William, "Wood--An Electric Generating Fuel in Vermont--A Procurement Point of View", Green Mountain Power Corporation, private communication, June 12, 1974.

In theory, and perhaps with improved forest management, Vermont's entire electricity requirements could be derived from wood. With the current price of fossil fuel hovering between $1.50 - $2.00 per million Btu, a competitive price for delivered green wood chips would be $10.50 per ton ($26.00 per cord, a stack of wood 4 Ft. X 4 Ft. X 8 Ft.)

The cost and benefit implications of a wood-fired electric generating plant for Vermont's forest industry, economy and environment will be internalized as part of the feasibility study.

The power plants operating on this type of fuel would have to be situated at "mine mouth." This is almost as restrictive as that required for location of an ocean thermal powered electric utility.

In view of the increasing awareness and concern with the political aspect, availability, reliability of supply, costs and the environmental and ecological effects of the fossil fuels, the conversion of organic materials into more readily useable fuel forms (like gas and light distillates) merits serious study.

In the conventional combustion (fire) process wood, straw or other vegetable matter is heated until it begins to release gases which burn and, in the burning process, heats other portions of the fuel so that more gases are released to be burned.

When organic material decays it yields useful by-products. The kinds of by-products depend upon the conditions under which decay takes place. Decay can be aerobic (with oxygen) or anaerobic (without oxygen). Any kind of organic matter can be broken down either way. Methane gas, an easily transported fuel, is one by-product of anaerobic decay. The efficiency and rate of decay can be optimized artificially. The kinds of organic material used as "feedstock" also governs the quantity of gas produced per unit of organic matter.

The utilization of organic wastes for the production of methane(2) should reduce the magnitude of the waste problem and be economically attractive.(1) Taking the present gas consumption as 2.2×10^{13} ft^3/yr., the total current gas demand could be met by processing 2.2×10^9 tons of organic wastes through anaerobic digestors. Conversions of the dry organic fraction of the solid waste generated annually would yield 25 to 40 percent of the gas demand.

Not all of this can be collected since the available organic wastes are not sufficient to satisfy the current gas demand; it is necessary to consider, as an alternate or supplementary feedstock, the growth of crops specifically for their energy content. This results in a system which converts solar energy to methane via photosynthesis and anaerobic fermation.

The Solar Energy Task Force report for the Project Independence Blueprint includes a section on bioconversion to fuels which can be paraphrased as follows:

> The overall goal of the bioconversion to fuels program is to produce as much as 15×10^{15} BTU's (2.5×10^9 barrels of oil equivalent) in the year 2000 from energy crops (terrestrial and marine) and from organic wastes (urban solid waste and agricultural residues).

To achieve this level of production, an accelerated program of R & D and subsidized early commercial production facilities may be required as the estimated price of energy from these organic sources is not expected to be less than about $2.00 per million/BTU during this period. This price does take into account credits for by-products in the form of food products and chemical feedstocks, which may be obtained in the production of biomass.

Energy planning systems are not expected to become economically attractive until the costs of alternative energy sources exceed the equivalent of $11 per barrel of oil.

There must be a sequence of steps before a reliable and economically viable system can be established.

Deriving clean fuels from biomass or waste organic materials is the only "renewable" method of fuel production known. Two important considerations are present. First,the number of possible forms of energy crops, and conversion processes is very large. Second, the degree of development of the different production and conversion processes varies greatly.

The Project Independence Blueprint study contains a schedule showing the anticipated schedule for the research and development program which will lead to Proof-of-Concept. They are reproduced as Appendix II.

An R & D program has to be formulated and completed that will develop the technology base for large scale fuel and energy producing systems for:

a) producing significant economic quantities of biomass (feedstock plantation)

b) converting this biomass into useful fuels and energy

The conversion processes will have two environmental consequences. Conversion of urban solid waste and agricultural residues (particularly feedlot wastes) will reduce many of the problems associated with disposal of these materials. Additionally, the residues from conversion of agricultural residues and energy crops may prove to be useful as organic fertilizers, soil conditioners or as animal food supplements.

On the other hand, conversion of urban solid waste may produce waste water and filter cake with little utility and some potential disposal problems.

The biomass stock is low in sulfur content and most other pollutants characteristic of fossil fuels. Non-point source pollutants associated with agricultural operations may present some problems, especially with regard to fertilizers and pesticides. The large use of irrigation water presents salinization problems.

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(1) Szego, George C. and Kemp, Clinton C., "Energy Forests and Fuel Plantations", Chemtech, May 1973.

(2) Schneider, T.R., "Substitute Natural Gas from Organic Materials", ASME 72-WA/Ener-7, July 1972.

(3) Green Mountain Power Corporation, Burlington, Vermont.

APPENDIX I

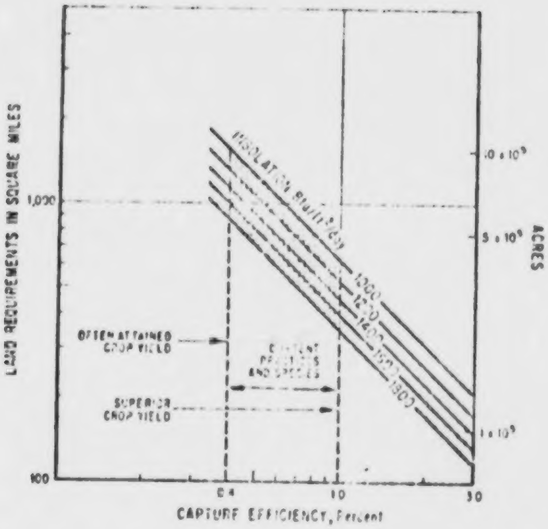

Figure 1. Land required for a 1000 MW steam-electric plant (35% efficiency, 75% load factor)

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APPENDIX I

Land requirements

The land requirements for energy plantations are manageable. This conclusion is supported by a comparison with the land bases that support kraft pulp mills in the South.

At the end of 1971 there were 26 kraft pulp mills in the South having a daily production capacity of 1000 tons or more of pulp (23). Assume that

—1.7 cords of softwood are required per ton of pulp

—pulp mills operate 350 days a year

—75 percent of their pulp wood requirement is supplied as round wood (23)

—softwood growth yields are, on a sustained basis, about 2 cords per acre per year (a relatively high average yield), then about 350 square miles of pulpwood forest will thus be required to support a 1000 ton per day kraft pulp mill. An area about this big will support a 400 megawatt electric generating station even if only 0.4 percent of the solar energy incident on it is converted to fuel value, as the estimate in the next paragraph indicates.

Assume that the thermal efficiency of a generating station fired with plant fuel is about 35 percent. This efficiency, which is low for modern stations fired with conventional fossil fuels, is about equivalent to 10,000 Btu per kilowatt hour. Further assume that the load factor of the station is 50 percent on an annual basis (approximately the national average). Under these conditions the energy plantation land area required to supply the fuel for the station will be about 370 square miles. The energy plantation required to support a 1000 MW base load generating station (75 per cent load factor) at various insolation rates and conversions of solar energy to fuel value will be about as shown in Figure 1.

It may thus be concluded that since the area for an energy plantation adequate to supply a generating station of a capacity in line with many modern stations is of the same order of magnitude as the land areas presently being managed for each of two dozen large pulp mills, areas of similar size can be managed for energy plantations without serious difficulty.

Economics

Adoption of energy plantations as a significant source of fuel will depend in part on the cost of the fuel produced, and in part on the convenience with which it can be utilized. The cost of producing fuel value in an energy plantation will depend on:

--the yield of fuel per unit area per unit time (i.e., on Btu per acre per year), and

--the cost incurred per unit plantation area per unit time (i.e., dollars per acre per year).

(1) Szego, George C. and Kemp, Clinton C., "Energy Forests and Fuel Plantations" Chemtech, May 1973.

SUMMARY OF KEY MILESTONES AND RELATED DECISION POINTS

FY	MILESTONE	DECISION POINTS
75	Initiate POCE: Process for Producing Methane Gas from Urban Solid Wastes (3)	Final Review Engineering Systems Study Evaluation of Process
		Evaluation of Response to RFP and Award Contract (3)
	Initiate Total System Studies of Promising Energy Farming Concepts (1,2)	
76	Initiate Total System Study of Promising Agri-Waste Energy Conversion Opportunities (2)	Review Panel Evaluation of Previous Engineering Systems Studies (2)
	Initiate POCE Design Studies for Agri-Waste Energy Conversion Systems (4)	As above plus Interim Results of Total System Study (4)
77, 78, 79	Complete POCE: Process for Converting Urban Solid Wastes to Methane	FY79 (1)
	Initiate POCE's Agri-Waste Energy Conversion Systems	FY77, FY78
	Complete Agri-Waste POCE's	FY79 (2,3,4) FY80 (1,2)
	Initiate Energy Farming System POCE's	FY77 (2) FY78 (2) FY79 (2)
80 - 85	Initiate Demonstration Projects:	
	Urban Solid Waste to Methane Process	FY80
	Agri-Waste Energy Systems	FY81
	Marine Energy Farm	FY81
	Terrestrial Energy Farms	FY 81, FY 82

Number in () refers to quarter of year in which activity is scheduled.

APPENDIX II (cont.)

FY	MILESTONES	DECISION POINTS
80 - 85	Complete Demonstration Projects:	
	Urban Solid Waste to Methane	FY82
	Agri-Waste Energy System	FY83
	Marine Energy Farm	FY85
	Terrestrial Energy Farm(s)	FY85, FY86

from Table 12 of the Report of the Task Force on Solar Energy of the Project Independence Blueprint Study, Federal Energy Administration, November 1974.

James W. Meyer
December 1, 1974

Monograph No. 9

MIT Energy Laboratory

HYDROGEN FUEL

Recently, hydrogen has received attention as a possible alternative fuel to natural gas, for the following reasons:

1) Reserves of natural gas are severely limited and are being depleted rapidly;
2) Reserves of petroleum, and especially tar sands and oil shale are somewhat limited, but the latter two are recoverable only at higher costs and are facing serious opposition from the environmentalists;
3) Reserves of coal are relatively large, but mining costs promise to rise steeply as increasing quantities required for liquefaction, fasification, etc., are mined from increasingly unfavorable deposits;
4) A clean gaseous fuel will apparently always be needed to fill the country's pipelines. Hydrogen is the prime candidate here if natural or synthetic methane becomes unavailable or unattractive; and
5) Today's indications are that electrical power generation in the long run will increasingly be taken over by nuclear plants of enormous size, operating in remote locations near large volumes of cooling water. There are indications that this electrical energy might be advantageously converted to hydrogen, both to supply the needed fuel gas and to obtain the economy of low gas transmission costs relative to electric energy transmission.

Hydrogen's suitability as a natural gas substitute derives from the following:

1) Hydrogen of high purity can be made by water-decomposition, so operated that only water and energy are consumed. The by-product oxygen produced can be safely vented into the atmosphere without pollution hazard. The raw material required, namely water, is

available in substantially limitless supply; and

2) Hydrogen burns to produce only water when combusted only with oxygen; thus, formation of the usual undesireable pollutants, namely CO, unburned hydrocarbons, sulfur compounds, and particulates, is entirely avoided. As when burning any fuel in air, nitrogen oxides will form in combustions when carried out at high enough temperatures. Formations of these undesired oxides can be minimized, as usual, by operating at lowest possible temperatures.

Hydrogen's characteristics as a fuel can be judged from the following:

1) Comparing on a volume basis, hydrogen has about 1/3 the heating value of natural gas. Thus, if methane saturated with water vapor shows a "higher" heat of combustion of 1000 Btu per cubic foot (60^{o}F, 30" water), hydrogen is 313 Btu/cubic foot under the same conditions;
2) Hydrogen's use involves hazards somewhat greater than with natural gas: its flammability limits (4% to 75% in air) are much wider than for methane (5% to 15%) or for any other gas, for that matter; its low viscosity relative to other gases means that hydrogen escapes more rapidly through a given leak; the energy required for ignition of an explosive mixture of hydrogen in air is smaller than for methane. Hydrogen burns with a substantially invisible flame, which could, however, be rendered visible with suitable additives. Hydrogen is colorless, but could be supplemented with the same odorizers (mercaptans) as natural gas;
3) With proper burner and settings, hydrogen can be burned in household appliances about as successfully as natural gas;
4) Hydrogen, unlike natural gas, undergoes "flameless" combustion when passed (mixed with air) through a process plate filled with a catalyst. The heat evolved in this porous plate is re-radiated; thus these plates act as "hot plates." Such heating may be of importance for appliances;
5) Hydrogen uniquely is an excellent fuel for fuel cells operating at near atmospheric temperature with aqueous electrolytes; and
6) Hydrogen can, of course, serve as fuel for properly designed

internal and external combustion engines.

Hydrogen can be used with relatively high efficiency in a fuel cell.

1) The efficiency of hydrogen use in a fuel cell is a sensitive function of current density, cell design, etc. It is probably possible to attain an 80% efficiency here in converting hydrogen's energy to electrical energy.
2) It seems probable that the energy efficiency of interconverting electrical energy and hydrogen is 80% either way. Thus, an overall energy efficiency of 64% in converting electrical energy to hydrogen and back again to electrical energy appears reasonable.

Hydrogen transmission through gas pipelines may present new problems:

1) A gaseous hydrogen pipeline grid, 130 miles long, is operated in the Ruhr by Chemische Werke Huls A.G., with diameters of from 6 to 12 inches and a design pressure of 250 psi. Seamless steel pipe (SAE 1015) is used, with no compressor stations needed. There is reportedly a 50 mile hydrogen line in South Africa. Air Products Inc. operates near Houston, Texas, a 15 mile long hydrogen line, 8" in diameter, at 200 psi;
2) There is a tremendous background of know-how on natural gas pipe lines, relatively little on hydrogen lines. Whether hydrogen could safely be put through existing natural gas lines and compressor stations, apparently remains to be established. There seems little doubt that pipelines designed specifically for hydrogen can be built using existing technology;
3) Hydrogen transmission costs by pipeline can only be approximated at this time. These transmissions cost per mile are a sensitive function of through-put (pressure and pipe diameters), pumping costs as influenced by fuel costs, and terrains as this affects capital costs. All these factors are optimized in pipeline design. It is to be remembered that costs also depend on the load factor;
4) Costs per mile of transmissions of 10^3 cubic feet of hydrogen, very roughly, will be about the same as for 10^3 cubic feet of natural gas, assuming total flows, pressure, etc., comparable. Thus, per million Btu costs for hydrogen are three-fold those for natural

gas. Very roughly typical costs of transmission of one-thousand cubic feet of natural gas (10^6 Btu) is around 2¢ per 100 miles in larger pipe. Thus, costs of transmission of one million Btu of energy as hydrogen would be 6¢ per 100 miles (6.8¢/1000 kWh/100 miles versus 20.4¢/1000 kWh/100 miles); and

5) Hydrogen might alternatively be transported cryogenically in tanks as a liquid, or in solid combination as a hydride. Such possibilities are highly speculative, and are "far out."

Hydrogen can be generated from water and electrical energy by electrolysis:

1) Water Electrolysis, whereby water is decomposed to gaseous hydrogen and gaseous oxygen, is an old art. Water electrolysis has never been an important source of hydrogen industrially, because of the high costs of the electrical energy required (roughly 90 kW hours for 1000 cubic feet of H_2 and 500 cubic feet of associated oxygen). Only in remoter regions of countries like Norway and Canada, where electricity has been available at 1 to 2 mills/kWh, has hydrogen been produced electrolytically for large scale use;
2) In this country, the enormous quantities of hydrogen consumed in petroleum refining, ammonia productions, etc., have come from reactions of steam with natural gas, petroleum fractions, and to a limited extent, with coal. By these routes, hydrogen is far cheaper today than by electrolysis. Of course, as fossil fuel costs increase due to decreased availability, electrolysis using relatively cheap electrical energy (from nuclear plants) will become more attractive;
3) Because of the low level of industrial interest, electrolytic hydrogen plants are not highly evolved, and cost data are not abundant or trustworthy. Designs have come typically from European engineering concerns, who are especially secretive. The Allis Chalmers Corporation in this country estimates investment costs (based upon an assumed advanced plant design) of $37,500,000 for a capacity of 44,000 lbs. H_2/hour (equivalent to 400,000,000 cubic feet/day, or 16.7 million cubic feet per hour. This plant cost is probably significantly underestimated,

but nevertheless is smaller by almost an order of magnitude than the costs of the large SNG Lurgi plants planned in this country;

4) Theoretical energy needs by electrolysis, when operating at or relatively near to room temperature, are 82 kW hours for 1000 cubic feet of hydrogen. Actual operations (all depending on cell design, current densities, temperature, operating pressures, etc.) are around 90 kW hours per 1000 cubic feet of H_2; and
5) By the Allis Chalmers design, operating costs have been estimated as follows:

Per day (400,000,000 cubic feet H_2/day)

Labor, Maintenance, etc.	$ 3,100
Energy, 36 x 10^6 kW hours @ ½¢	180,000
Depreciation @ 5%	5,000
	$189,000

The foregoing shows the overriding importance of the electrical energy cost component. Note that theory shows this cost cannot be reduced more than about 10% at most.

Hydrogen production from water plus energy available only as high temperature heat has been proposed, but success here is by no means assured.

1) While design problems will be significant, nuclear reactors could probably be designed to make large quantities of heat available at as high as 1000° C. Very little increase in this temperature is foreseeable at this time. This heat would be available in cooling tubes somehow passing through the reactors. For safety, the heat absorbing medium flowing through these tubes, in which air endothermal reaction presumably occurs, would have to be as controllable and "reliable" as water in boiler tubes.
2) Various reaction series can be proposed whereby, when operating between 1000° and 25° C (the surroundings temperature, or close to it), water can be made to decompose to its elements. Nothing would be consumed in this operation except heat and water, making

it a "thermal equivalent" of electrolysis, in which only electrical energy and water is consumed.

3) In theory, there are many reaction schemes whereby the above can be accomplished. Whether, however, either energy efficiency or equipment costs can be superior to those of an orthodox nuclear power plant operating on this same high temperature heat, plus a water electrolysis plant, remains to be demonstrated.

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William J. Jones
December 1, 1974

Monograph No. 10
MIT Energy Laboratory
GAS TURBINES

A burner/boiler/steam engine (steam turbine) combination is a class of external combustion engine that is basic in the electric power industry. The gases from the burning fuel heat a fluid which drives a rotating machine connected to an electric generator.

A gas turbine is another class of external combustion engine. The gases from the burning fuel drive a rotating machine (turbine) directly. For electric power production, the gas turbine is connected to an electric generator.

Gas turbines have relatively low capital cost, short installation time, and can respond to load changes quickly. Large numbers have been recently installed by the electric utilities. The original motivation was to provide spinning reserve and peak power.

With the increased demand for electricity, the gas turbines are often used for periods of 2000 hours per year and more. The extended utilization of gas turbines has been a factor in the trend of the electric industry to install combinations of gas turbines and steam plants to generate electricity.

THE PATTERN OF THE PAST

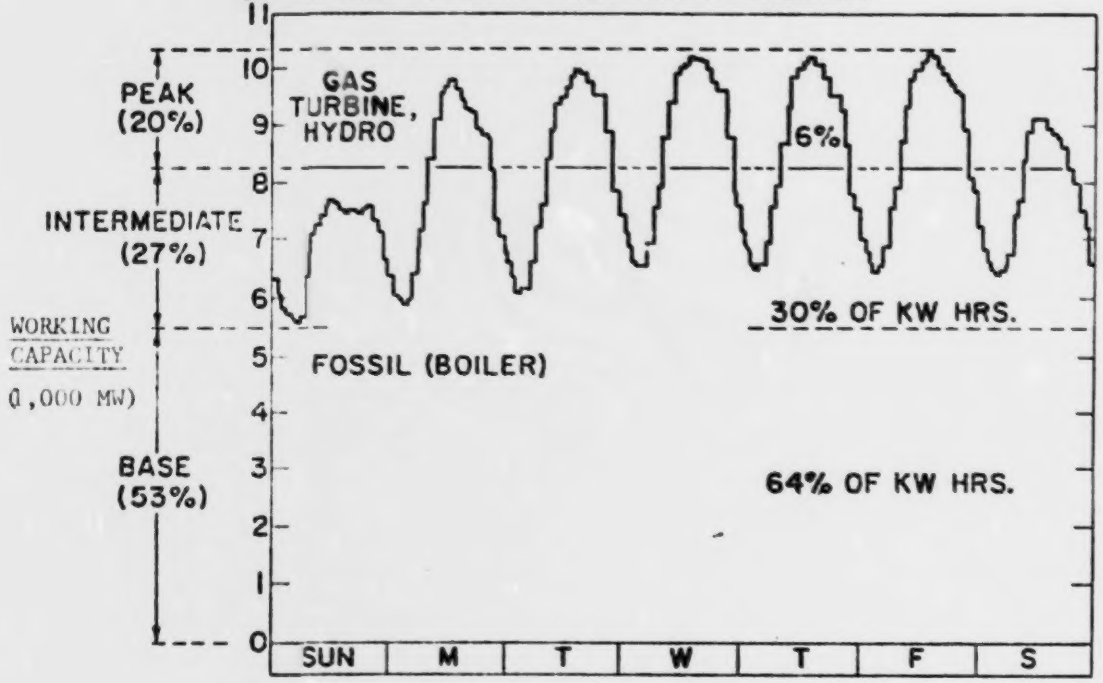
The load pattern is a key determinant in the selection of generation technologies and in consequent fuel requirements. A typical composite weekly load pattern taken from the Federal Power Commission's 1970 National Power Survey report is shown in Figure 1.

Up to the early 60's fossil fuel fired under-boiler generating plants served in almost the whole range of load. New efficient plants were operated as nearly as possible full-time; older, less efficient, partially written off plants were used in the intermediate load range in which 12-14 hour operation, 5 days a week as an operational norm; still older, smaller plants would be placed on load only a few hours a day at the peaks. Hydro capacity, where available, would be used near the peaks also because of quick start-up capacity.

FIGURE 1

ELECTRICITY LOAD CURVE U.S.

(A TYPICAL UTILITY COMPOSITE EXAMPLE)



THE PATTERN OF THE FUTURE

A pattern for the future is shown in Figure 2. Until 1981 the data are taken from the National Electric Reliability Council's Fall 1972 report of utility plans. Much of this capacity for 1981 is already existent or under construction (especially the nuclear and the high pressure supercritical fossil). The forward projection for nuclear is the most recent AEC estimate: the total capacity projection is simply a run-out at the historic 7% per year growth rate, divided into peaking, intermediate and base load in the same ratio as for the 70's.

Important aspects of this pattern are:

(1) Base load capacity most likely will be 50% nuclear within 8-9 years and perhaps 75% within 15 years.

(2) Within 12-15 years (1985-1988) essentially all base load capacity will be of "nondemotable" types (i.e., nuclear and supercritical steam). From this point onward, all intermediate load capacity growth will have to be filled by the installation of new equipment-fuel systems specifically optimized for part-time service.

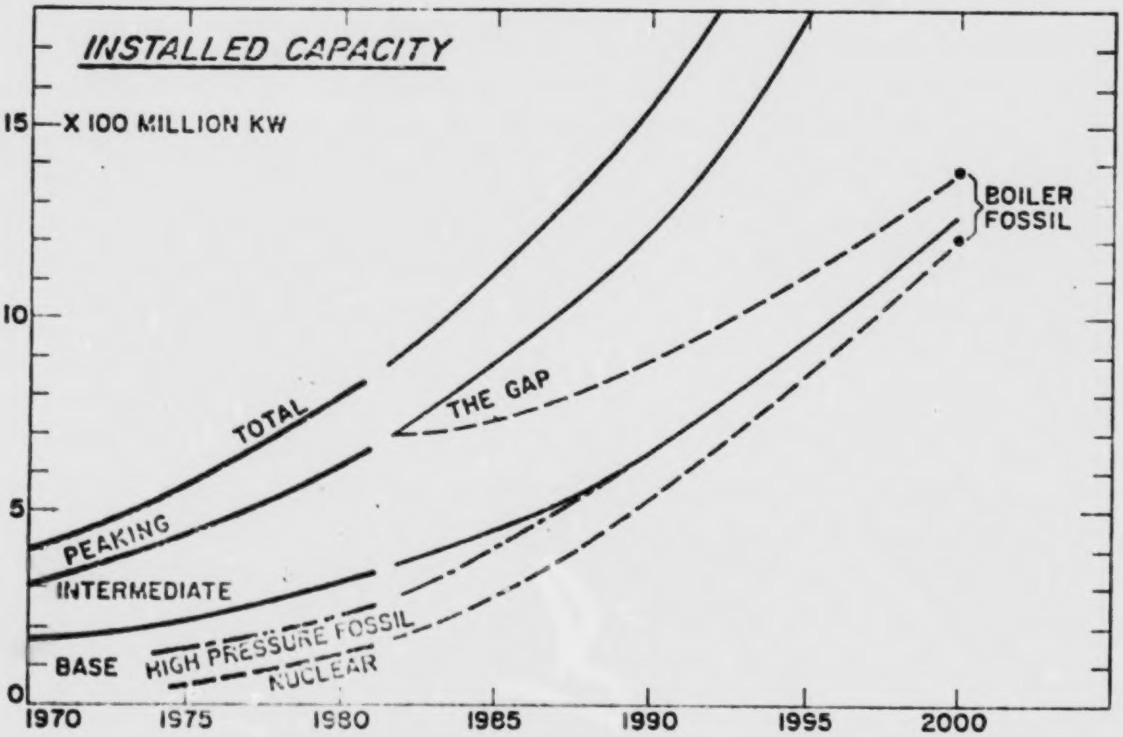
(3) This new type intermediate load capacity "GAP" begins to open in the early 80s.*

A technology which might fill this "GAP" is the "gas turbine-steam turbine combination," also known as STAG (STeam And Gas Turbine) or PACE (Power At Combined Efficiency).

Due to the delays in commissioning dates for new base load stations which have been caused in the last few years by environmental considerations, regulatory problems and design and construction delays, some utilities have decided to ensure themselves against a shortage of base load capacity in the mid-70's by beginning to order new "combo" units now, since they can be had with a 2-3 year delivery time. This movement began in 1972 when 6300 MWe were placed on order. Since the forces which caused this advance ordering are continuing, a more realistic expectation for the "GAP" could take place in 1974 instead of in 1981, as shown in Figure 3.

* A basic assumption in this calculation was that the annual commissioning of new under-boiler type capacity for base load will drop to a negligible amount by 1981. This is the only assumption which is consistent with present technology trends, present ordering trends, and present utilities' planning. The validity of this assumption, and the consequences of various kinds of deviation, are explained in the Addendum.

FIGURE 2



"Gap between projected installed capacity of electric power plants and demand."

Source: Federal Power Commission

This implied growth of gas turbine-steam turbine combination capacity is plotted directly in Figure 2, 3, 4 and 5.

In the combined system, a fuel is burned and the hot gases therefrom drive the gas turbine. The exhaust (the hot gases) from the turbine, still at a very high temperature, are used to generate steam. This steam then drives a conventional steam turbine. The gas turbine and the steam turbine each drives its own electric generator.

The present efficiency of a gas turbine alone is about 25%. The efficiency of a fossil fired steam plant may be about 35%. The thermal efficiency of a combined gas turbine/steam turbine power plants which are due to come into operation this year will be slightly below 40%.

The efficiency of the steam turbine portion of the combined cycle system has, for all practical purposes, reached its limit.

It is anticipated that gas turbine efficiencies can, within a decade, reach 35% and, in another decade, 40%. The advances in thermal efficiencies described above can only be achieved if the improvements in high temperature materials, turbine cooling techniques and aerodynamic design derived from current aircraft engine programs can be translated into higher maximum operating temperatures and cycle pressure ratios in industrial gas turbines for electric utility applications.

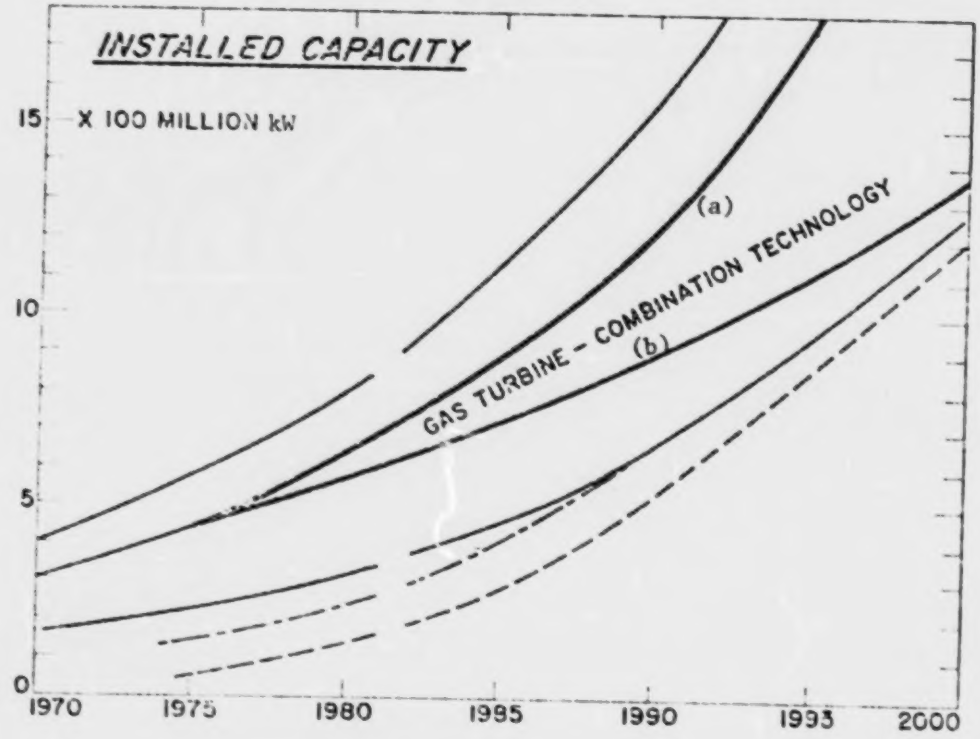
The combined cycle systems could reach efficiencies between 40% and 50% at the end of this decade and during the next decade could move towards 55%.

Since conventional nuclear power plants have efficiencies around 32% it is reasonable to ask why one would choose plants with a thermal efficiency limited to about 32%, rather than those presently 40% efficient and expectations of reaching 50% to 60%.

Special Problems

There are a number of considerations. Some are important only in light of assumed objectives and others represent constraints that greatly limit the number of opportunities to use gas turbines alone or in combination with steam and turbines.

FIGURE 3



Recommended scheme for filling gap between unfilled demand (a) and capacity (b).

Source: Federal Power Commission

This implied growth of gas turbine-steam turbine combination capacity is plotted directly in Figure 4.

FIGURE 4

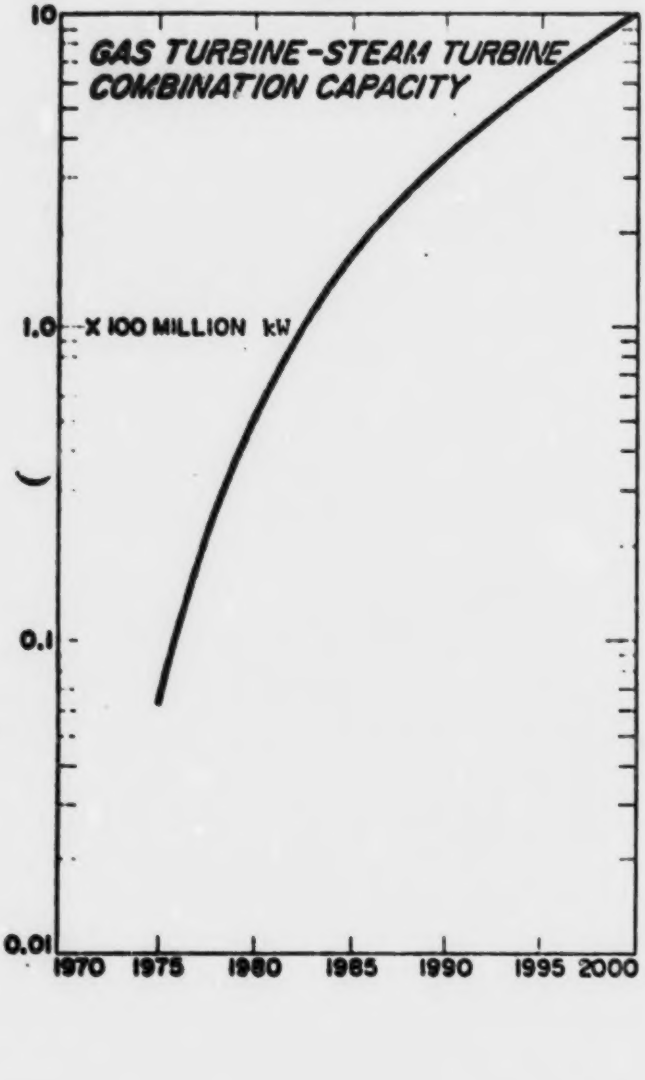
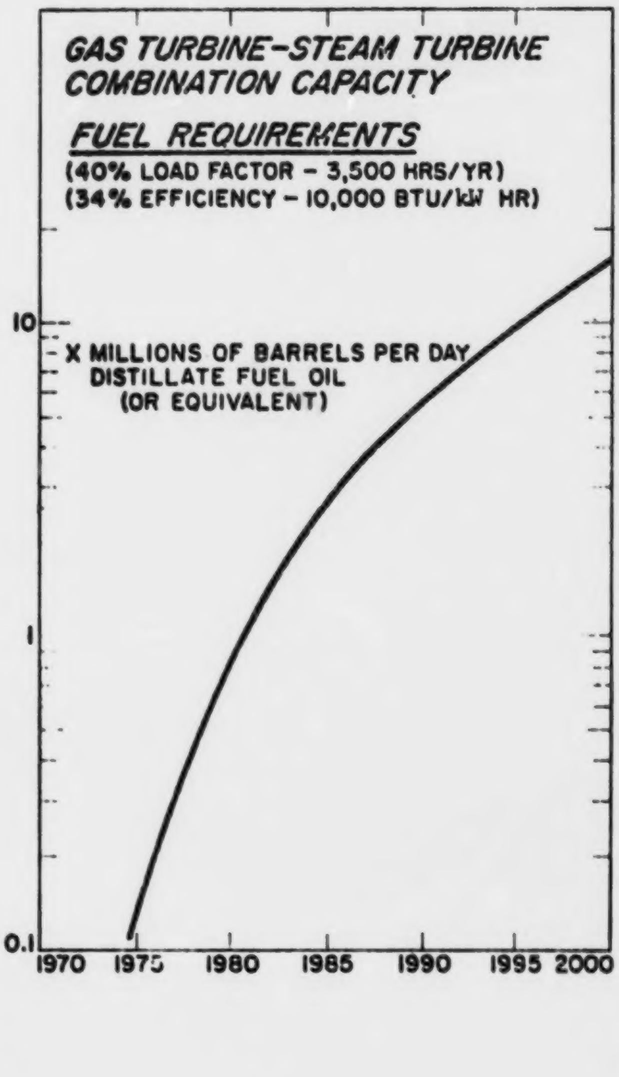


FIGURE 5



Only light petroleum distillates such as numbers 1 and 2 and diesel fuel, natural gas, butane, propane and low Btu gas, free of harmful alkali and sulphur compounds, can be used in advanced gas turbines. Heavy residual fuels which are used in conventional fossil fixed electric power plants would seriously reduce the maximum operating temperatures in order to avoid erosion, ash deposition, vanadium corrosion and sulfidation of turbine blades and vanes. Coal cannot be burned directly.

If more readily available coal, heavy oils, etc., are to be used, they have to be converted into a clean liquid or gaseous fuel. The conversion of heavy oil and coal into a clean high or low Btu gas results in a loss of some of the energy in the original fuel, hence the overall efficiency is reduced. It is necessary, therefore, to use fuels which are in short supply, or await the development and construction of facilities which can convert more abundant, but unsuitable, dirty fuels to clean fuels.

Size of Gas Turbines

Present gas turbines are of sizes up to around 60 megawatts; however, it may be expected that the maximum size of industrial gas turbines may soon double. With a power turbine operating at 1800 RPM instead of 3600 RPM, units up to around 250 MW could be developed.

It has been suggested that one could develop an integrated system (coal gasifiers, low and high temperature cleanup processes and combined cycle systems); however, the development would have to be preceded by a study devoted to identifying the areas of technology needing exploration in order to realize the advantages of the integrated system. Then there would be a need to further analyze the various identified technologies in order to define actual programs needed to bring them to commercial realization.

An electric generating power plant is a complex system in itself. To include a complete coal gasification or liquifaction plant would require a new organization of engineers and technicians at each plant. Disposal of the residue (ashes, etc.) at or from the electricity generation site may not be feasible.

Gas Turbines and Pollution

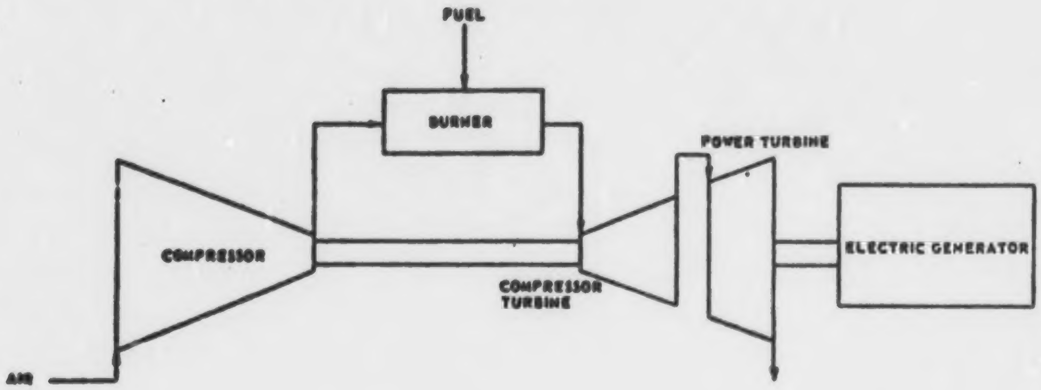
Simple and complex cycle gas turbines can be used where the availability of cooling water is limited. Combined cycles provide means to reduce the amount of heat rejected at the condenser per unit of electric power produced. Since gas turbines have to burn clean fuels free of sulfur, alkali and lead content, nitrogen oxides are the main pollutants to be concerned with. The combustion of fossil fuels with air results in the formation of nitrogen oxides in all power systems. Further, the control of NO_x in the stack gases is quite complex, since nitric oxide is relatively unreactive. Thus, the most attractive method of NO_x control is to limit their formation in the combustion products and in their subsequent cooling. The amount of NO_x formed depends on the conditions in the primary combustion zones and on the subsequent temperature and concentration distribution of the combustion products.

The combustor primary zones are operated at near stoichiometric conditions and recirculation is used to enhance complete combustion. High primary zone temperature and long residence time promote NO_x formation. In stationary power plants, water injection can be used to cool primary combustion gases before much NO_x is formed. Premixing of fuel and air can also be used to obtain lean primary combustion, achieve lower flame temperature and reduce the NO_x formation. The appreciable mass flow of low Btu gas to air ratio should allow good premixing and good sub-stoichiometric combustion. It would therefore appear that the NO_x emissions achievable in advanced gas turbines can be maintained at a low permissable level without compromising turbine performance.

The site location considerations of a combined-cycle and fuel processing plant are many orders of magnitude more complex. The sources of fuel (there should be a minimum of two), required transportation facilities environmental impact of the fuel processing plant and disposal of the unique effluents (keeping in mind that the residues are not conventional ash) and the overall system economics are issues that would be added to those present for a conventional utility.

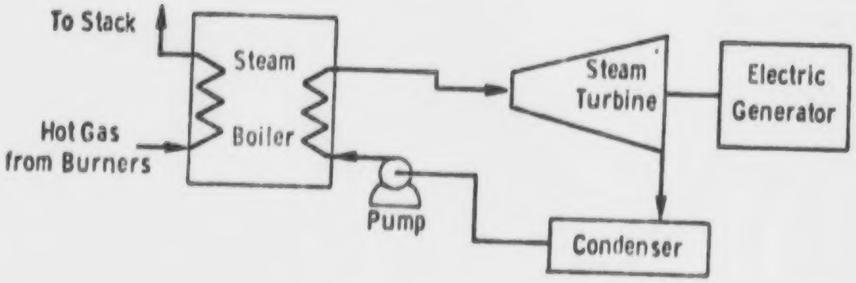
It is possible to generate 2000 megawatts with a plurality of small combined systems. The economics and complexity of such an installation need detailed study.

Major technology changes, environmental and societal concerns are altering electricity generation and its fuel consideration. The requirement for clean gaseous or liquid fuels for gas turbines and conceivably other technologies too, will have to be sufficient to warrant the time and effort for research, development and construction stages. Gas turbines fuel requirements are in competition with present domestic, commercial and industrial demands. Clean fuels in necessary quantities to eliminate the need for nuclear or high pressure supercritical, or other sources of energy, will not be available for two decades.


FUEL
BURNER
POWER TURBINE
COMPRESSOR
ELECTRIC GENERATOR
COMPRESSOR TURBINE
AIR

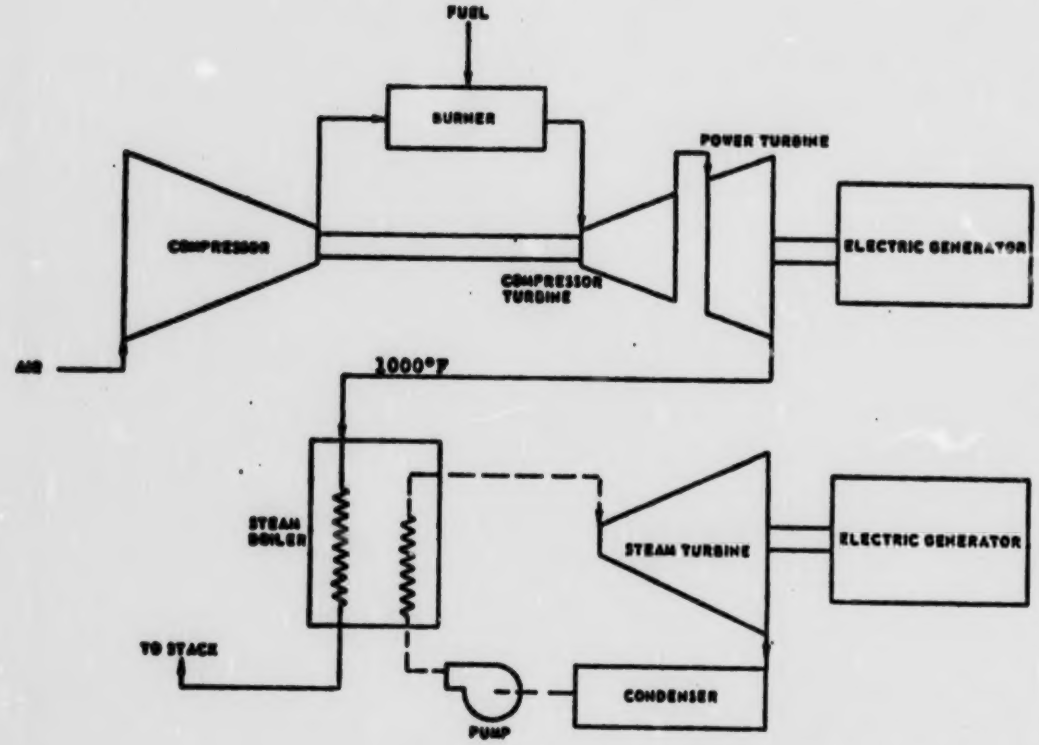
Gas Turbine

Figure 6


To Stack
Steam
Boiler
Hot Gas
from Burners
Steam
Turbine
Electric
Generator
Pump
Condenser

Steam Turbine

Figure 7


FUEL
BURNER
POWER TURBINE
COMPRESSOR
COMPRESSOR TURBINE
ELECTRIC GENERATOR
AIR
1000°F
STEAM BOILER
STEAM TURBINE
ELECTRIC GENERATOR
TO STACK
CONDENSER
PUMP

Combined Cycle System

Figure 8

James W. Meyer
December 1, 1974

Monograph No. 11

MIT Energy Laboratory

FUEL CELL GENERATION OF ELECTRIC POWER

To solve the problem of providing electric power for space vehicles and for certain military application, the federal government provided funds for fuel cell research which peaked at about $16-million in 1963 and had fallen off to about $3-million in 1970. Only one company, Pratt & Whitney Aircraft, division of United Aircraft Corporation, East Hartford, Connecticut, persisted in the direction of providing a commercialized fuel cell system with potential application to electric utility systems.

The basic fuel for fuel cells is hydrogen and oxygen which, when reacted in a cell, produces electric power and forms water as a by-product. A fuel cell power plant also contains a reformer and an inverter. The reformer is a chemical reactor which converts the primary fuel (e.g. natural gas, distillate fuel oil, methanol) into hydrogen for use in the fuel cell with oxygen derived from the air. The inverter changes the direct current output of the fuel cell into alternating current at the frequency and voltages required for distribution and use in conventional electric utility circuits.

Commercial applications approached by the Pratt & Whitney program are three related but different size units:

1) On-site conversion of natural gas to electricity
2) Supplementary power plants to central station facilities (25 to 100 megawatts)
3) Electric power for remote locations and unattended operation (10 to 200 kilowatts)

Only Westinghouse Electric Corporation, Pittsburgh, Pennsylvania, has investigated the use of fuel cells for central station generation. Westinghouse has no present program for the commercialization of such units.

On-site generation of electricity for residences and small businesses has received most field testing thus far. Thirty-five natural gas companies formed a Team to Advance Research for Gas Energy

Transformation (TARGET) and have installed nearly sixty 12.5 kilowatt fuel cell power plants at 37 locations in the United States and Canada. A goal of the program was to demonstrate the commercial feasibility of providing all utilities for a residence or small business with but a single fuel: natural gas. The same units, perhaps with a different reformer technique to accomodate other primary fuels, have application also in the remote location category.

The program for the commercial development of supplementary power plants of a unit capacity of twenty-six megawatts (enough to provide electricity for a community of 20,000 people) has been supported by a group of electric utilities, and by Pratt & Whitney's own funds.

The electric utility industry plans to employ these units for dispersed power generation, a non-traditional approach, that locates generating units within the distribution network which disperses pollution sources, lessens transmission line requirements, and reduces reserve requirements. An advantage of the system is its agility in responding to changes in load. Units respond "instantaneously" (in less than a cycle) to a step load increase (or decrease) from zero to 100% of rated power. This makes the system particularly suitable to meet peak demands on a utility system which it can do more efficiently than can conventional peaking equipment.

The 26 MW FGC-1 Fuel Cell Power Plant being developed by Pratt & Whitney has a fuel equivalent heat rate of 8500 Btu/kWh at part load, and at full 26 MW output, 12,000 Btu/MWh reflecting a loss of plant efficiency at peak loads. This is to be compared with that of a conventional steam plant usually taken to be 10,300 Btu/kWh. Sulfur compounds are potentially harmful to Powercel because they poison the reformer catalyst. Both unsaturated and heavy hydrocarbons cause carbon formation in the reformer. Ammonia (nitrogen) deposits in the fuel cell, and water reduces the charcoal capacity. Liquid fuels suitable for FGC-1 are limited to:

Jet A
Jet B
Naptha
No. 2 Heating Oil

or the following gases:

Natural gas
Process gas
Propane
Butane
Hydrogen

The FGC-1 thus is competing for the premium fossil fuel and its effective heat rate exceeds that of a conventional steam system at its maximum rated continuous power of 26 MW.

Pratt & Whitney production plans are to deliver the first production generator in mid-1977 and to establish a manufacturing capability to deliver at least 50 generators by year 1980. These are the only fuel cell systems at this or comparable power levels this close to commercial service.

To replicate the generating capacity of a 1200 MW power plant with these fuel cell systems, operating at half rated power for maximum fuel efficiency, would require 90 units, nearly two years' production in the 1980s.

Northeast Utilities, Hartford, Connecticut has conducted studies of utilization economics. In particular, they compared the annual production costs of a 250 MW nuclear system with a 250 MW fuel cell power plant as a function of fuel cost at the substation. The base load fuel cell has lower annual production costs for fuel costs up to $.80/MBtu. The nuclear fuel price was taken to be $.21/MBtu. Fuel cell capital costs were taken to be $165/kw and those for the nuclear plant as $325/kW. If the nuclear installed cost is taken to be $400/kW, the break-even fuel cost is greater than $1/MBtu. Twelve-dollar-a-barrel oil is a fuel cost in excess of $2/MBtu. Fuel and construction costs have changed dramatically since these studies were performed. The above figures are quoted only to indicate the economic context in which the study was done.

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W.J. Luecket, L.G. Eklund and S.H. Law, "Fuel Cells for Dispersed Power Generation," Paper presented at the IEEE meeting in New York, 1973.

David C. White
December 1, 1974

Working Paper No. 12
MIT Energy Laboratory

CONSERVING, FINDING AND DIRECTING ENERGY RESOURCES*

Introduction:

The oil embargo of the fall of 1973 coupled with the rapid price escalation of OPEC controlled foreign oil prompted the United States government to undertake a national program aimed at reducing dependence on foreign petroleum. The program is called Project Independence and the FEA is currently leading a major study to develop a blueprint to define strategies consistent with national economic goals and energy resources. While the national program has not been announced, the preliminary reports from the FEA, and other reports such as the MIT Energy Laboratory study "Energy Self-Sufficiency: An Economic Evaluation"(1), and the NAE study "U.S. Energy Prospects, An Engineering Viewpoint"(2), all show that domestic self-sufficiency carries with it a very high price for energy fuels plus additional environmental costs that have not been thoroughly evaluated. The United States thus finds itself facing a major change in its historical position of abundant cheap energy.

The response to this change requires careful evaluation of the future use of both United States and world energy resources.

In recent years both popular and professional attention has been focused on the exponentially growing United States and world gross national products, energy consumption and population. Two divergent groups have taken opposing strong positions. The "Neo-Malthusians" views are symbolized by Paul Ehrlich(3) in his stand against population growth and Jay Forrester(4) in his prediction of cyclic catastrophe from over-use of resources, food, and related inputs to an industrialized society. An alternative "Neo-Malthusian" view is that of the environmentalists which is that pollution from products of industrialization such as particulates, chemicals, radioactivity, and heat will overload the natural ability of the earth to maintain an equilibrium in which man can live in his projected state of growing industrialization and population. The other view is that of the "Technology Optimists" characterized mainly by resource economists as typified by Harold J. Barnett(5) who look at the historical prices of mineral resources and food in the marketplace and show that for over one hundred years they have been decreasing in real dollars, with technology improvement offsetting depletion effects. With price the economist's measure of scarcity they conclude there is no shortage of these resources: the rate of technical advance has outrun any real resource limitations either through ecomanagement and substitutes, or drastically lowering the risk of extinction, or promotion and recycling.

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* Presented at the panel discussion of Financial Executive Institute's 43rd annual international conference at Honolulu, Hawaii, October 6 - 9, 1974

A resolution of these opposing views is not possible since each is based on fundamentally different premises. The "Neo-Malthusians" tend to deal primarily with physical quantities, which are surely finite on a finite earth. The "Technology Optimists" tend to focus more on economic measures dealing with relative price and productivity which in theory reflect all physical constraints. The fault of the former is that it usually projects farther into the future than realistic projection can be made, particularly considering possible technology improvements and societal changes. The fault of the latter is that economic criteria using any reasonable interest rate gives negligible weight to events more than 20-30 years into the future and focuses only on short range criteria, with current production and consumption being the driving forces. For effective or optimum resource allocation and utilization a medium term view lying somewhere in between the two extremes is probably required. A viable theory to deal with medium term projection and resource evaluation is yet to be developed and is a major challenge to planning effective resource utilization.

Historical Trends:

The consumption of energy in all forms has grown steadily in the U.S. along with the GNP and the population since the beginning of the industrial revolution. In fact, in the last 100 years energy consumption has grown by a factor of 20, of which a factor of 5 has been due to population growth and a factor of 4 due to energy use per capita. The increased use of energy per capita has accompanied increased industrialization, and has been further accelerated by the general economic level (affluence) of society as a whole. The average growth rate of energy utilization for a century has been 3%, yet in 1973, even with shortages in the last quarter and major efforts to reduce energy use, the annual growth rate for all energy was 4.8%, while petroleum, our domestic fuel in shortest supply, grew at a rate of 5.2%. This trend is not new, in fact, 1972 was similar with petroleum consumption growing at 8%. The decade of the sixties also showed a steadily growing demand for energy fuels, particularly petroleum products in all forms. The first significant break in this trend has occurred in late 1973 and 1974 as a result of a short run shortage coupled with large price changes for petroleum products.

An important consequence of the increased prices of fuels is beginning to emerge. During the period of energy shortages there occurred a major reduction of energy consumption in all sectors. During the six months, January through June 1974, the consumption by primary fuel type shown in Table I occurred. The consumption of electricity generated from these primary fuels for 1974 is shown as a weekly percentage change over 1973 in Figure I. These data show that the combination of shortages, high prices and national requests for consumption have reduced the total consumption of energy fuels by 2.6% for the first six months of 1974 over 1973 and reduced the 1974 growth rate for electricity to approximately zero over 1973. This marked shift from steadily increasing energy consumption to one of a slight decrease is an important indicator if it is due to changes in consumption patterns.

Some indication of possible change is obtained from the data on gross national product (GNP) as shown in Table II. For the first two quarters of 1974 there was an increase in GNP in current dollars but a slight decrease when corrected to constant 1958 dollars. There is then a 0.6% decrease in real GNP for the first six months of 1974 and a decrease of 2.6% in total fuel consumed. This corresponds to a net 2% gain in energy productivity (i.e. energy consumed per unit of output) for this period. This is not an enormous gain but does show some short range response of the total system to the markedly changed character of the energy supply-price patterns during the first part of 1974.

An important additional factor does appear in Table I. The fuel that has changed most markedly in price is oil (approximately tripling) and this has shown the largest decrease (-5.6%). Both shortages and higher prices for oil appeared during this six-month period.

TABLE I

U.S. ENERGY CONSUMPTION, 1974 versus 1973

	Six Month Average, January-June		Change 1974 from 1973	
	1974	1973		
BOE*, in millions of barrels/day				Percent
Oil	16.4	17.3	-0.9	-5.2%
Natural Gas	11.8	12.3	-0.5	-4.1%
Coal	6.4	6.2	+0.2	+3.2%
Hydro	1.6	1.5	+0.1	+6.6%
Nuclear	0.5	0.4	+0.1	+25%
Total	36.9	37.9	-1.0	-2.6%

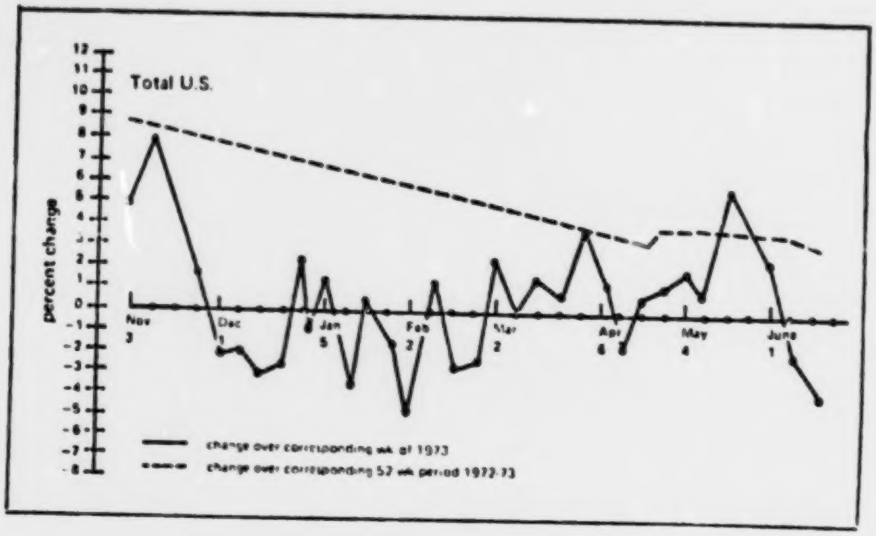
Source: The Oil Daily, Friday, August 2, 1974 (6)

* Barrels of oil equivalent

FIGURE 1

ELECTRIC OUTPUT IN THE U.S.

Through June 15, 1974, in Kwh



Source: Electric Light and Power, E/G Edition, July 1974.(7)

TABLE II

GROSS NATIONAL PRODUCT

Billions of Dollars

	Quarters			
	1st	2nd	3rd	4th
Current Dollars				
1973	1248.9	1277.9	1308.8	1344
1974	1358.8	1383.5		
1958 Dollars				
1973	832.8	837.4	840.8	845.7
1974	830.5	828		
Percent change:	-0.16%	-1.1%		
Six month change:		-0.6%		

The short run reduction in total oil consumption cannot at this time be used to reliably estimate either short or long term price responsiveness of various petroleum products. Average changes are misleading since the tripling in crude oil prices transfers through to different products and consumers in markedly different ways. Residual oil prices used for industrial processes and electricity generation which in early 1970 were below crude prices, have more than tripled in price and now often sell at or above crude oil prices. Gasoline has increased about 40% at the pump, up approximately 20¢ per gallon which corresponds to a doubling of the non tax price. Electricity in the Eastern Seaboard where residual oil is the primary fuel has seen prices increase by 50% because of fuel pass thru charges in rate structures. These price changes and the reduction in consumption over historic 7% growth rates for electricity shown in Figure I appear to be important trends for future policy to improve domestic supply-demand balance.

The possible influence of high prices and shortages is further accented by Table III which shows the cumulative consumption of electricity for January through August 24, 1974 by region. The regions most impacted by high residual oil prices are the Atlantic Seaboard and the South Pacific Coast. They show substantial decrease in electricity consumption, i.e., New England (-5.4%); Middle Atlantic (-3.4%), and Pacific Southwest (-4.5%).

However, since the removal of the boycott and the return of plentiful fuel supplies, albeit at substantially higher prices, there has been a gradual return to normal fuel patterns not disturbed by shortages. As stable supplies return there is growing evidence that the higher fuel prices are not bringing forth a demand responsiveness to price in the relatively short term that was observed when the shortage existed.

Table III which shows the weekly demand for electricity for the

TABLE III

Weekly Output Aug. 24

40,299,000,000 kwhr

Aug. 17 39,299 Aug. 10 37,685

	Latest week over 1973	Cum. year to date	52 weeks to date
Total U.S.	+ 5.6	0.0	+ 1.5%
New Eng.	+ 5.3	- 5.4	- 1.9
Mid. Atlan.	+ 9.6	- 3.4	- 1.1
Cent. Ind.	+ 7.3	- 0.7	+ 1.4
West. Cent.	- 2.4	+ 2.3	+ 2.6
Southeast	+ 6.9	+ 0.2	+ 2.6
So. Cent.	+ 4.3	+ 5.1	+ 5.2
Rocky Mt.	+ 5.0	+ 5.7	+ 5.8
Pacific			
NW........	+ 9.0	+ 4.3	+ 1.5
SW........	- 1.7	- 4.5	- 2.7

Latest seasonally adjusted index 169

Previous week 166 Year ago 159

Source: Edison Electric Institute

(From Electric World, Spt. 15, 1974)(8)

week of August 24, 1974 shows in almost all regions an increase in demand over the same week in 1973. This is the peak period of summer air conditioning load and is a period of high and historically increasing demand. Even at higher prices, a high growth in demand occurred on the Atlantic Seaboard.

A somewhat similar pattern for petroleum products is shown in Table IV. The high demand for electricity shows up in the increased demand for residual oil. The vacation demand for transportation shows up in the increased use of gasoline (+2.3%) and jet fuel (+5.6%) over the similar period of 1973. One thus observes a return to somewhat normal demand growth occurring as the specter of shortages disappears. The growing surplus of gasoline during the summer, and the softening of gasoline and other petroleum prices is possibly leading the way back to historic energy consumption practices. The long run response to increasing prices is yet to be determined but the promising short run price responsiveness of the first six months of 1974 may well prove to be anomalous. If this is true, the implication of price elasticities calculated by many econometric models from data in periods of decreasing prices such as the work of Hudson and Jorgenson discussed later, may be open to serious question and, if so, pose major problems for programs of conservation based on decreased consumption and increased energy productivity.

Domestic Energy Supply Potential:

The domestic resource base of fossil and nuclear fuels is still large compared to even present consumption levels. Resources are always difficult to estimate for at least two reasons. First, until they are actually discovered they must be estimated from geological data alone, and second, once

TABLE IV

PETROLEUM PRODUCTS DEMAND FOR AUGUST, 1974 VERSUS 1973*

Demand, b/d: (4-week avg.)	Latest week (9-6-74)	Year ago (9-6-73)	% Change
Motor gasoline	7,067,000	6,906,000	+ 2.3
Middle distillates	2,313,000	2,633,000	-12.2
Jet fuel	1,043,000	988,000	+ 5.6
Residual	2,785,000	2,454,000	+13.5
Other products, etc.	3,475,000	3,600,000	- 3.5
Total demand	16,683,000	16,581,000	+ 0.6

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* Source: Oil & Gas Journal, September 16, 1974 (9)

discovered, the amount recoverable depends upon both price and technology. Any discussion of resources tends to be a mixture of true resource uncertainty and confusion as to the underlying assumptions on recovery methods and prices. The recently released A.P.I. reserve data on petroleum has this problem, because it assumes a price substantially below the current market and thus underestimates current reserves. Even though the resource base is large, there are many technological and economic problems to be overcome to deliver these energy resources to the marketplace in a form that is useable by current equipment, and environmentally acceptable to society.

One problem with which the U.S. is faced today and is central to policy formulation for the rest of the 1970's is: What portion of the U.S. energy demand can be met with domestic supply at what prices, utilizing which fuels, requiring what technology, and requiring what lead times to bring it into effective utilization? A supply curve of domestic fuels dealing with these factors is not available nor fully able to be estimated. Neither is the demand curve known nor can it be effectively estimated since the U.S. history of energy utilization has been developed in a framework of decreasing real costs for energy supplies, except for the last year. Mixed into both the supply and demand picture is the further complication of the last decade of growing environmental impact of energy production and utilization with which government and society generally are struggling to deal effectively. Thus the basic information to make joint predictions of future supply-demand responsiveness is not available and decisions must be reached under conditions of high uncertainty where costs and risk are extremely large for both producers and consumers of energy fuels.

The MIT Energy Laboratory has used current econometric models to estimate supply responsiveness of the three major fuels by the end of this decade at prices from $1.25 to $2.00 per million Btu's*. These studies indicate that the above prices for domestic petroleum generate supply responses of about + 10% over 1973 production. For this same price range the domestic natural gas supply increases approximately 25% under a pricing policy of a jump in price followed by steadily increasing prices for new gas. The coal responsiveness is 0% to 25% over current consumption depending upon sulfur requirements, strip mining practices and transportation rate structures. The electricity contribution from nuclear power will double. Thus the total domestic supply for the price range of $1.25 to $2.00 per million Btu is, by the end of the 1970's, increased approximately 20% over the 1973 domestic production. These substantially higher prices over pre-1973 prices have a supply response that is relatively limited during the decade of the 1970's.

The demand response to this same range of prices has also been estimated.(1) At the $1.25 per million Btu price the aggregated demand is up 25% while at $2.00 per million Btu the demand is up only 15% over 1973 demand with 1973 inputs running above 15% of total demand. The demand-supply clearing price for domestic fuels, assuming maximum responsiveness of both supply and demand, seems to be above $2.00 per million Btu in 1973 dollars by the end of the decade. This figure is probably low considering both the physical and political constraints to be overcome.

The precision of these estimates is subject to substantial error and can only be considered as general guidelines. They indicate, however, that domestic supply-demand balance by the end of the 1970's can only be obtained at a high price, if at all. In addition to price, it also requires major changes in government policy such as increased pricing of natural gas, liberal coal mining policies with minimum environmental constraints, and expanded leasing policies on federal lands for all energy fuels. The combination of high prices and policy changes raises the question of what other options are available.

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*For a detailed analysis of the complex factors of supply-demand and new technology, see reference(1). All cost figures are in 1973 prices.

Potential alternates to the conventional fossil fuels are synthetic fuels - low and high Btu gas from coal and syncrude from coal or oil shale. Gasification and liquefaction of coal are both proven technology developed primarily by Germany in the 1940's but allowed to effectively languish in the last three decades because of the price advantage of natural petroleum products. Currently, major efforts are underway to update and improve this technology to improve process efficiency and lower costs so as to make the large quantities of domestic coal and oil shale an effective domestic supply source.

Most of the new technologies are in the pilot or prepilot plant stage. Thus, processes are in a state of flux and capital costs as well as total costs are subject to substantial uncertainty. To establish some measure of the state of the synthetic technology the MIT Energy Laboratory(1) evaluated current literature on those processes and developed a set of comparative costs to the extent it was possible to do so. Using a standard plant size of 250 x 10^9 Btu per day equivalent, the capital cost of all synthetic fuel plants supplying methane or a syncrude seem to be remarkably similar and range from 350 to 400 million dollars per daily 250 x 10^6 Btu. The cost of the products also cluster in the range of $1.25 to $1.75 per million Btu which includes a 15% charge for capital. The capital requirements for thoseplants is high since it takes approximately four dollars of investment to generate an annual million Btu's of product whose cost at the plant is estimated to range between $1.25 and $1.75.

These costs contain neither profits nor allowance for risk. If for this high risk and a capital intensive industry, a pre tax return on capital at 25% is required to generate the necessary capital, the price must contain an additional $1.00 to cover the capital investment of $4.00. This translates into a price of $2.25 to $2.75 per million Btu at the plant. Thus a reasonable price estimate of a synthetic fuel seems to be between $12.50 and $16.50 per barrel with the higher price being more probable.

Recognizing that there are large uncertainties in these estimated prices, the data strongly indicate that the synthetic fuel industry needs major technological improvements and cost reductions to be an economically acceptable energy supply alternative.

In addition to price there is a further critical problem. A gasification plant for coal that produces 240 million cu. ft. per day (250×10^9 btu/day) requires an input of 15,000 tons of coal per day or 5 million tons annually. It takes 12 such plants to generate one trillion cu. ft. of methane annually. It takes 72 similar size liquefaction plants (40,000 bbl./day and 10,000 tons coal/day) to yield one billion barrels of syncrude annually. A 1% contribution to the estimated energy demand by the end of the decade is approximately 0.5 billion annual barrels of oil equivalent. Even this modest contribution would require 36 syncrude plants consuming 120 million tons of coal annually. The time required to design and construct a typical syncrude plant once protype experience is obtained is approximately 5 years and requires 1.5 million man hours of technical labor and 10 million man hours of craftsman and manual labor. The major architect-engineering firms of the U.S. face doubling to tripling in size in this decade to meet projects already under contract for electric power plants and conventional fossil fuel facilities.(1) This raises a serious question of the potential expansion capability of this sector to take on the radically new technology of a synthetic fuel industry.

Considering the current state of technology, the long proving time for new technology, the large technical and craftsman manpower inputs to the complex plants for synthetic fuels, and the large numbers of plants required to significantly contribute to domestic demand for energy fuels, one is forced to conclude the synthetic fuels industry as a major energy source is many years into the future - probably well into the 1990's.

The simplest summary of the synthetic fuel technology is that it is truly difficult to produce in man-made plants liquid and gaseous fuels from solid fossil fuels that are equivalent to those that nature produced and concentrated in natural reservoirs over millions of years. The synthetic fuel industry is going to be truly hard pressed to compete with natural petroleum products and cannot do so in the 1990's.

Other energy sources not requiring fossil fuels as the primary energy input are nuclear, solar and geothermal sources. Solar energy can be used for space conditioning in residential and commercial buildings utilizing current laboratory technology. Because past low prices for energy have made solar heating uneconomical, there has been no industry developed to supply solar heating components. As prices rise these conditions are changing. The time, however, to establish a new industry supplying essentially a consumer-dominated market is long and fraught with difficulties. Consumer-dominated products incur large distribution costs and carry a high introduction cost entailing substantial risk. Merely calculating materials of construction and labor costs under ideal conditions vastly underestimates the economic break-even point of a new consumer product. This has often been done in predicting the economic point at which solar power can compete with other fuels. Add to this the variability of solar power, hence the need for energy storage and usually supplementation by other sources and one has a complicated picture for a solar industry development. The time will be years and probably decades.

Solar energy for electricity generation is even more complicated and is always fighting the capital and land costs inherent in a low intensity-diffuse and variable power source. Economic solar power for electricity generation is still in the exploratory research phase.

Geothermal energy from dry and wet steam reservoirs is exploitable with known technology. Geological explorations to locate sources, the handling of corrosive vapors, and the disposal of waste heat because of the low temperatures involved are all problems. Geothermal steam has a utility whenever it exists and is being developed today. Geothermal steam, however, cannot supply more than a very small fraction of energy demand. Deep hot rock geothermal sources are an interesting energy source but no technology exists to utilize them effectively. It is still a research area.

Nuclear fission power is the only non-fossil fuel source currently available that is backed by a fully developed industry structure to manufacture, install, operate and deliver power to consumers. The past twenty years of development and operating experience has brought this industry to a point of maturity where it can be a major energy supply source. There are problems of siting, licensing, safety, construction costs, and social acceptance which must be overcome for this industry to fully develop its potential. To the present heated and often irrational dialogues on both sides, there is little that can be added in a short paragraph other than to draw a comparison between this developed industry now facing many problems including social acceptance and the as yet infant synthetic fuel industry. There seems to be no inherent advantage of synthetic fuel plants over nuclear plants in terms of costs, environmental impacts, desirability to have in densely populated urban areas, etc. To believe the synthetic fuel industry can develop faster, with fewer problems, and be more acceptable is mixing fact with fantasy. Such fantasy is always expensive as past experience has proven many times over.

Energy Productivity and Conservation

The productivity of industry is determined by the factor inputs which are traditionally taken as capital and labor. The cost of natural resource inputs, particularly energy, for most industries have been low relative to labor and capital costs. A long history of abundance of resources coupled with national policy to subsidize resource development (depletion allowances) and resource consumption (price regulation) has effectively maintained resource availability at low market prices. The United States has developed its industrial base and pattern of consumption in this historical framework of abundant low priced resources and one consequence is that the United States is the world leader in resource consumption per capita.

The changing availability of resources by the combination of increasing depletion of domestic resources and cartelization of some world resources is changing the pattern of both resource availability and prices.

The long history of cheap and abundant energy has set a pattern of United States energy consumption in which capital costs of energy consuming equipment are a larger fraction of total costs than fuel costs. This pattern pervades the residential-commercial sector, the transportation sector, and the industrial sector, including even the energy intensive primary metals, petrochemicals, food products, etc. The price changes of the last year where the price of crude oil has approximately tripled has brought forth both real changes in energy productivity, and studies of energy utilization which indicate what may be technically and economically feasible for future energy use practices.

Returning first to the influence of shortages and price changes there is evidence for the first time in history, except for wartime periods, that the growth rate in energy consumption has been reduced. In the transportation sector the 1974 consumption of gasoline was below 1973 levels until August -- when consumption in the two years was approximately equal. The combination of driving restraint, transportation mode shift, and high prices produced a reduction in energy consumption. In the residential and commercial market during the period of the shortages the demand for electricity in New England was down approximately 15%. In the Northeast a combination of thermostat adjustments and home improvements resulting from restraint and price increases yielded a 30% decrease in the demand for heating oil in the winter of 1973-74. In the industrial sector typically a 10% to 15% reduction in energy consumption was achieved through improved scheduling of product flows, reduction of heat losses in faulty equipment and minor improvements in processes. Such small gains were essentially available on a one-time improvement spurred by shortages and increased prices. A fundamental question is which of those type reductions are sustainable, by what incentives, and how do the long-term economics of increased energy production compare with the economics of increased supply development? Several studies are available of potentials for improved energy productivity in energy intensive industrial processes.

The report "Potential for Effective Use of Fuel in Industry" prepared by the Thermo Electron Corporation in April 1974(10) identifies potential savings in five of the most energy intensive industries. They conclude that a one-third savings is possible in these industries by the use of 1973 technology and that substantial additional savings are possible through the development of new technologies. A summary of their results is shown in Table V.

The upper limit of theoretical possibility was determined by tabulating a theoretical minimum energy consumption for each industry based on thermodynamic availability*. This minimum energy requirement is for most processes shown in Table V approximately 10% of the present energy consumed. The minimum bound set by the theoretical limit is certainly not obtainable but this bound does help to show what might be expected by research and additional capital investment. As a rough estimate a factor of three gain in overall effectiveness of energy consumption in industrial processes would be pushing the practical limits quite hard, and the theoretical factor of 10 is essentially impossible. The fact that 1973 technology can reduce energy consumption by one-third (i.e. use only 66% of the current energy input per unit of output) indicates that the existing technology is in fact well along the way toward reasonable practical energy effectiveness if it is used.

There are two generalizations that arise from a technological evaluation of energy savings in industrial processes. One basic approach is to obtain more work from the fuel or more heat delivered per unit of fuel consumed and requires generally a topping cycle (or bottoming cycle) that results in mechanical shaft power used directly or to produce electricity.

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* Thermodynamic availability is the maximum amount of work that can be done by a system starting from a given state and ending up in stable equilibrium with the atmosphere. (10).

Table V (10)

COMPARISON OF SPECIFIC FUEL CONSUMPTION OF KNOWN PROCESSES WITH THEORETICAL MINIMUM FOR SELECTED U.S. INDUSTRIES

	1968 Specific Fuel Consumption (Btu/ton)	Potential Specific Fuel Consumption Using Technology Existing in 1973 (Btu/ton)	Theoretical Minimum Specific Fuel Consumption Based Upon Thermodynamic Availability Analysis (Btu/ton)
Iron and Steel	26.5×10^6	17.2×10^6	6.0×10^6
Petroleum Refining	4.4×10^6	3.3×10^6	0.4×10^6
Paper	*39.0×10^6	*23.8×10^6	**Greater than -0.2×10^6 Smaller than $+0.1 \times 10^6$
Primary Aluminum Production***	190×10^6	152×10^6	25.2×10^6
Cement	7.9×10^6	4.7×10^6	0.8×10^6

* Includes waste products consumed as fuel by paper industry.

** Negative value means that no fuel is required.

*** Does not include effect of scrap recycling.

The other is the use of heat recuperators to reduce waste heat and increase overall efficiency. Both are capital-intensive investments but involve essentially well known technology.

Four cases have been analyzed which show the cost and energy savings possibly by a technological change(11). The four cases are (1) heat recuperation for a refinery, (2) topping cycle to produce mechanical work for an ammonia plant, (3) SO_2 scrubber to allow use of high sulfur coal, and (4) double glazing of residential structures. The energy savings and costs for these four cases are summarized in Table VI.

At prices of around $\$1.50/10^6$ Btu the investments in equipment to reduce energy consumption in the refinery and ammonia plant are reasonable investments even after reducing the savings by the taxes paid on profits resulting from the increased energy productivity of the plants. In large energy intensive industries these examples indicate that current prices should stimulate capital investment in increased energy productivity. Approximately 45% of U.S. energy consumption is in the industrial sector and of this 45% is used to produce process steam and 30% direct combustion heating. Investments in technical improvements can save 10% to 30% of this energy, which would result in a 5% to 10% savings in total current consumption.

The savings in residential heating by the use of double glazing is not as cost effective as the two examples for energy savings in industrial plants. The returns on the investment for double glazing are similar to current bank rates and provide little incentive for the investment. Considering that residential and commercial space heating and air conditioning account for approximately 25% of the total U.S. energy consumption makes this an important area for developing incentives for stimulating such invest-

Case Study (11)	Fuel & Price	Capital Investment per daily BOE saved and annual savings		After tax return (15-year straight line depreciation - 48% taxes)	Comments
Refinery (heat recuperation)	residual oil or crude oil $1.50/10^6 Btu	$6,600 capital $3,300 annual saving		28%	Excellent investment
Ammonia plant (turbine topping cycle)	natural gas $1.50/10^6 Btu $2.00/10^6 Btu	$24,000 capital $ 8,400 annual saving $11,500 annual saving		 15% 21%	Below $1.50/10^6 Btu not a good investment. Not feasible at current low price of natural gas in the Southwest.
Double glazing residential structure (Norway climate)	fuel oil $2.50/10^6 Btu	$31,400 capital $ 5,300 annual saving		(No taxes charged) 10% (15-yr depreciation) 13.5% (30-yr depreciation)	Does not account for improved comfort factor and hence possibly reduced thermostat settings
SO$_2$ Scrubbers 40% duty cycle of plant	2% sulfur coal $10-$15/ton delivered to Eastern markets	Capital Cost $14/annual BOE $58/annual ton	Operating Cost $1.40/annual BOE $5.82/annual ton	Cost of cleanup $0.56/10^6 Btu $13.50/ton (assumes 15% capital charge)	Allows use of Eastern high sulfur coal at competitive prices to low sulfur coal or low sulfur oil

TABLE VI (11)

COMPARISON OF FOUR ENERGY CONSERVATION SCHEMES ments if conservation is the goal.

The use of the scrubbers to make high sulfur coal available as shown in Table VI is a possible investment at current high prices for petroleum. The potential for using high sulfur Eastern coal in Eastern markets by adapting a scrubber technology helps to relieve dependence on foreign fuels. The major difficulty with this technology is that it is still not fully developed and requires substantial lead time for its installation. The unproven nature of the technology and hence uncertainty of cost projections may require special incentives for this technology to develop and be adapted rapidly. Considering that 20% of the total energy consumption is coal and that over half of this is high sulfur coal the gains for keeping high sulfur coal a viable fuel source are large.

The above four cases do not include any study of the transportation industry which consumes 25% of the total energy. Here examples of increased energy efficiency are obvious since automobiles are currently on the market with fuel efficiencies ranging from below 10 miles per gallon to as high as 40 miles per gallon. With the national average for fuel efficiency around 12 miles per gallon the issue is clearly how to shift consumer purchasing habits. The gasoline shortage brought a short term shift in the last quarter of 1973 and first quarter of 1974 but this seems to be abating somewhat. Elimination of shortages, price reductions on larger size automobiles and a lack of well designed domestic small cars with engines and gear trains matched for high efficiency all have blunted the short trends to lighter more efficient automobiles. A factor of two in total efficiency is technically possible and incentives to stimulate such changes in consumer buying and use is an area where large potential gains exist.

Another major factor that is impacting the effectiveness of energy utilization is the move to clean up the environment. The Clean Air Act and the regulation of thermal discharges into water bodies are resulting in significant losses in energy efficiency. Emission control from large combustion facilities is requiring SO_2 scrubbers and particulate removal or shifts to clean fuels. The result is a loss of 2 to 10 points in efficiency or the use of scarce and expensive fuel. The control of emissions from automobiles has also resulted initially in reduced gasoline mileage of the average vehicle fleet. The limiting of thermal discharges in water bodies particularly zero thermal emissions requiring cooling towers, lead to losses in power plant efficiency of 2 to 5 points. In many instances where environmental regulations are being imposed a negative impact of energy efficiency has occurred. This is not due to physical laws in most instances, but does require that designs be modified to meet energy efficiency and also environmental emissions. A coordinated attack on both is a requirement if the environmental improvement doesn't occur at the cost of energy effectiveness. Planning and adequate time for change is essential.

In all areas of energy consumption there appear to be no technological limitations that rule out increases in energy productivity. In some cases there is the need for increased investments to improve energy productivity. In others change in buying and use habits are required. The most effective way to effect changes in each case involves data that is often not available plus complex sociological and technological trade-offs involving incentives, price changes, and usually long lead times for change.

Economic Models of Energy Demand

Forecasting energy demand has been a primary objective of energy supply companies throughout their history. Until recently the best projections have been essentially trend extrapolation modified by consumer incomes and growth in real GNP. Recently economists have focused substantial effort on more effective demand projections that included technological change, price changes, as well as the influence of real income and GNP. The most advanced model of this type is the DRI model of Hudson and Jorgenson(12). This model has been used to check the estimated growth scenarios prepared by the Ford Energy Policy Project(13).

The DRI energy model is presented in detail in the DRI report to the Energy Policy Project: "Energy Resources and Economic Growth," DRI, September 30, 1973(12). The model is based on an interindustry model of the U.S. economy in which production and consumption are broken down in the following pattern:

(i) Production is classified into nine sectors, each of which is represented by a production submodel. These nine sectors are agriculture (together with nonfuel mining and construction), manufacturing, transport, services (together with trade and communication), coal mining, crude petroleum and natural gas extraction, petroleum refining, electric utilities, and gas utilities.

(ii) The nine producing sectors purchase inputs of primary factors - imports, capital services and labor services.

(iii) The nine producing sectors must also purchase inputs from each other, e.g. manufacturing makes purchases from transport and the transport sector makes purchases of manufacturing output.

(iv) The nine producing sectors then sell their net output to final users - personal consumption, investment, government and exports.

These components are then integrated within an interindustry, or input-output model. The feature of input-output analysis is that transaction flows are brought into consistency so that each sector produces exactly that amount needed to meet final demands as well as the intermediate demands from other producing sectors. The critical feature of the DRI energy model is that the patterns of input into the producing sectors, as well as the final demand levels, are functions of prices.

The DRI model was used to examine and compare the general economic environment corresponding to the three alternative energy growth patterns being studied by the Energy Policy Project. These growth patterns are (i) historical growth where past energy supply and demand patterns are assumed to continue into the future, (ii) "technical fix" growth where energy conservation practices and known energy saving technologies are incorporated into production and consumption patterns to the extent possible within existing life styles and economic organization, and (iii) "zero energy growth" (ZEG) where, in addition to the technical fix measures, changes in life styles and economic structure are introduced in order to move towards a situation of constant per capita energy consumption.

The results of simulations of U.S. economic growth over the 1975-2000 period for energy supply and demand conditions involving moves from historical growth patterns to an "energy technical fix" growth path, and from this to a "zero energy growth" path yielded the following main conclusions(14):

(i) Substantial economies in U.S. energy input are possible within the existing structure of the economy and without having to sacrifice continued growth of real incomes.

(ii) This energy conservation does have a non-trivial economic cost in terms of a reduction in real income levels vis-a-vis the historical growth position; in 2000 real income under technical fix growth and zero energy growth are both about 4% below the historical growth figure.

(iii) Adaptation to a less energy intensive economy will not have a cost in terms of reduced employment, in fact it will result in a slight increase in demand for labor. This, with the reduced real output, means that labor productivity is reduced, and correspondingly, real wages are slightly lower in technical fix or zero energy growth than in historical growth.

(iv) Adaptation to a less energy intensive economy will not have a cost in terms of total capital requirements; in fact, technical fix or zero energy growth should require slightly less total capital input than historical growth.

(v) The shift to reduced energy use will result in an increase in rates of inflation from a predicted 3.8% a year under historical growth to 4.1% under zero energy growth.

The quantitative economic changes involved in the move to technical fix or zero energy growth are summarized in Table VII.

TABLE VII(14)

Summary of Differences Between Growth Paths
(percentage difference in the level of
each variable between growth paths)

	Historical vs. Technical Fix		Historical vs. Zero Energy Growth		Technical Fix vs. Zero Energy Growth	
	1985	2000	1985	2000	1985	2000
Real GNP	-1.64	-3.78	-1.61	-3.54	0.03	0.25
Price of GNP	2.00	4.81	2.26	6.03	0.25	1.17
Employment	0.90	1.52	1.25	3.32	0.35	1.77
Capital input	-1.02	1.83	-0.88	-1.17	0.15	0.67
Energy input	-16.6	-37.7	-19.3	-46.1	-3.2	-13.4

The DRI study of the Ford Energy Policy Project scanning to the year 2000 indicates only minor economic consequences of reduced energy consumption. Inherent in these projections are the exogenous impacts of technological change in the energy coefficients of the input-output table. A detailed investigation of the technical feasibility of changes implied by the model was not done, although other studies of the FEPP could be useful for such analysis. The model was designed so that price changes would drive the system by being the trigger mechanism for changes in energy coefficients.

The zero growth scenario to the year 2000 projects a 46% decrease in energy consumption with less than a 4% decrease in historically projected GNP. This means an increase in energy productivity or energy shifts corresponding to a factor of 2. The use of 1973 technology in the industrial sector fully utilized was projected in Table IV to have potentially a 1.5 factor improvement in energy productivity. The DRI model thus indirectly assumes a mix of consumption shifts and process development or even invention between now and the year 2000 to give the gain in energy technology the economists have charted in this study.

The DRI projection that the economy does not need to be severely impacted by coordinated programs in reducing energy consumption is a challenge to both industries and technologists that may not be easy to meet.

There is another factor in the DRI model that is cause for concern. There is substantial price elasticity derived from past data in a period of decreasing prices in real terms. If the short range lack of response to price which is now starting to show up after the shortages have disappeared is a true indicator the estimated price elasticity from past data

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may be over-optimistic. Thus only price driven changes in energy use patterns and development of new technology may not yield the results indicated by the model.

Taxes of Natural Resource Producers

The best known tax provision affecting the energy industry is percentage depletion. Under the income tax provision other industries are permitted to deduct the cost of capital assets that are used up in production (usually called depreciation). Natural resource producers, however, have the privilege of treating a part of their income as tax-exempt, through percentage depletion, even if it far exceeds the cost of the assets (the wells or mines) being used up.

Percentage depletion is important for oil and gas. These products have the highest percentage depletion rate - 22 percent of gross income. Percentage depletion is based on the value of resources as they come out of the ground, and only to a minor extent applies to the value added by processing and transportation. The percentage depletion rate for uranium is also 22 percent. The rate on oil shale is 15 percent; on coal it is 10 percent.

Percentage depletion has some limitations. The allowance can only be applied to 50 percent of the net income from the property. Further, a taxpayer using percentage depletion gives up the opportunity to deduct cost depletion on some relatively small part of the actual costs that were incurred in developing the mineral property. Finally, percentage depletion is slightly reduced in value for many taxpayers because, since 1969, those who use it may be subject to a minimum tax. For oil and gas the net benefit overall is about 15 percent of the gross income from producing the natural resource; for uranium it is about 10 percent; for coal, about 5 percent.

Further income tax relief arises from special rules that allow current deductions for intangible drilling and development costs for oil and gas and certain exploration and development costs for other minerals. The differential benefit occurs because capital investments in other businesses are deductible only gradually, as the investment asset wastes away. A current deduction is worth more than a deduction spread over the life of the asset because of the "time value" of money. As a rule of thumb, the current deduction is twice as valuable.

The special tax benefits of percentage depletion, deduction of intangibles for oil and gas, and the normal investment credit for tangible drilling costs are equivalent to an investment credit of 49 percent. An analysis of the tax benefits for investment in mineral production which expresses the outcomes in relation to capital investment indicates that these benefits are in the general neighborhood of a 50 percent investment credit for oil, gas and coal.

Natural-resource tax provisions each have important differences. The differences arise in part because percentage depletion is based primarily on the value of resources as they come out of the ground; in general, it does not apply to the value added by refining, transportation, wholesaling, and retailing. The tax benefits of expanding drilling and development differ greatly among resources. In general, oil and gas production entail a relatively high share of capital cost compared with labor costs; production of coal, uranium and oil shale entail a relatively low capital cost compared with labor cost.

If all the savings from the natural resource tax provisions were passed along to the consumer (say a steam electric power plant) in the form of price reduction, the percentage reduction in fuel cost for electricity generated from each fuel would be approximately:

Oil	13.2%
Natural Gas	11.5%
Coal	3.4%
Gas from Coal	1.4%
Uranium	2.8%
Oil from Shale	4.5%

These differences in delivered prices as related to the tax benefits are one flaw of the present income tax provisions since energy incentives work very unevenly among the different resources that go into energy production.

The critical features of the tax treatment of foreign operations of the oil and gas industry are these:

1. The foreign tax credit is allowed for payment of taxes to the host countries (which are members of OPEC), even though it is dubious whether these charges are income taxes.

2. Percentage depletion and the deduction of intangible drilling expenses are allowed for foreign operations.

The allowance of percentage depletion and intangible drilling deductions on foreign oil production is a complex problem because of the total pattern of foreign taxes on oil. Foreign taxes on oil are greater than the U.S. tax on oil would be even if U.S. tax law disallowed percentage depletion and intangible deductions on foreign operations. These payments to host countries jumped astronomically during 1973 from about $1.50 per barrel to $7 per barrel -- the government take in Saudi Arabia on Arabian light 30° oil.

Under our present system of foreign tax credit for income tax (or taxes "in lieu of" income taxes), credit is extended to all charges imposed by OPEC governments. The form of the OPEC charge is a hypothetical income and cost calculation that amounts to a flat charge without regard to actual profit. The OPEC charge stipulates that about 20 percent of the payment to OPEC will be called a royalty, which is only a deductible cost to the oil company and not eligible for the foreign tax credit.

Foreign tax credits are far greater than the amount allowed against income from producing oil and gas. Under certain circumstances, the excess foreign tax credit can be used to reduce U.S. tax on other foreign income. The result is that the extension of the natural-resource tax advantages to foreign operations provide U.S. oil and gas companies operating in the OPEC area with some tax advantages other than those derived from producing oil and gas. This is shown graphically in Table VIII where an average tax of 39% exists for all industry but only 11% using current law for the petroleum producing industry.

A natural question is what is the influence of the reduced taxes and who shares the revenue shared. One effect of percentage depletion and deduction of intangibles on the oil market is an increase in the desire of companies to invest in more oil production.

A necessary ingredient for more exploration and development is acquisition of drilling rights on lands with oil or the prospects of oil and gas. Because the supply of land with oil prospects is limited, the increase in bidding should drive up royalties.

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TABLE VIII (15)

Alternative Effective Tax Rates on Oil and Gas Corporations compared to All U.S. Corporation, 1968 (corporations with net income only)

Account	All Corpor. Actual 1968 ($bil.)	Corporations in crude petroleum & natural gas Actual 1968 ($mil.)	Adjusted to present law ($mil.)
Income subject to tax	81.4	4,651	5,222
plus excess depletion	4.9	2,990	2,421
plus excess of depreciation of intangibles over tax deduction	.6	420	420
less foreign tax in excess	.6	(500)	(317)
Equals economic income	86.3	7,561	7,747
Income Tax before credits	39.7	2,400	2,673
less investment credit	2.4	196	196
less foreign tax credit	3.7	1,609	1,792
Equals tax after credit	33.6	576	881
Tax after investment credit but before foreign tax credit, as percent of economic income	43%	29%	32%
Tax after all credits as a percent of economic income	39%	8%	11%

Sources: *Statistics of Income, Corporations, 1968*. U.S. Treasury Dept., Internal Revenue Service. *The Tax Burden on the Oil and Gas Industry*, Houston Petroleum Industry Research, Inc., 1972. *The Petroleum Industry's Tax Burden, Taxation with Representation*, Arlington, Va., 1973.

The critical characteristic of the supply of drilling prospects is the "elasticity of supply." Davidson, Falk, and Lee(15) have developed an ingenious analysis of the relationship between royalty payments and supply elasticity. Their conclusion is that the supply situation for onshore U.S. drilling is such that the landowner share of net rents (that is, income in excess of drilling cost, including a normal return on capital) is about 25 percent; for offshore drilling on the U.S. outer continental shelf the landowner share is close to 40 to 50 percent.

The proposition that oil companies retain some of the economic rent is supported by statistics. McDonald's data show, for example, that in the production business oil companies earn better than normal profits. This evidence indicates that the benefits of percentage depletion are divided in the following way: 40 percent to increased royalties, possibly 10 percent to increased after-tax profits of oil companies, 50 percent to price reduction.

CONCLUSION

The previous sections have looked briefly at current energy consumption patterns, alternate energy supply potentials, energy productivity and conservation, energy-economic demand forecasting models, and energy taxes. Even though the analysis undertaken of each of these topics is relatively superficial certain major characteristics of the U.S. energy system can be identified:

1. Many incentives in effect for a long period of time and still operating with respect to domestic energy resource development reduce energy prices.

2. The regulations that have been developed in the last decade to maintain a clean environment have increased energy consumption or shifted

demand to the more scarce fuels.

3. The regulation and taxes developed for transportation have favored high energy consumption modes and have kept total costs from being reflected in the price paid by the user.

4. The regulation of the utility industries has ignored the marginal costs and prices of competing energy sources in rate setting such that some energy sectors are subsidized and demand artificially stimulated.

5. Investments to increase energy productivity and conserve resources are effectively biased negatively by some subsidies that reduce cost of capital for energy supplies and others that reduce the cost of energy use for some sectors of energy consumers. The bias is at least a factor of two for many energy suppliers and possibly even higher for some consuming sectors, particularly the automobile.

6. The technology exists for markedly improved productivity of energy in most industrial sectors and for most consumer operated equipment. The time to change the capital stock of equipment and the use patterns of industry and consumers is long and can be more effectively measured in decades than in years.

7. The supply of energy fuels is large both domestically and world wide. The basic issue in pricing and use priorities for energy is not resource availability in the near term but a mix of environmental issues and economic efficiency both domestically and world wide.

The first issue that must be faced in addressing the questions of conserving energy resources is why conserve? The national policy since the start of the industrial revolution has been to exploit resources to improve the U.S. standard of living. There is growing reason to doubt that the historic practice of subsidizing energy suppliers or segments of energy consumption is a wise policy. If this is so many changes are required in government taxing policy and regulations that allocate costs among consumers. The movement away from subsidies that stimulate energy consumption may be enough to develop more efficient resource utilization but this is by no means a certainty. The difficulty of incentives or regulations for consumption practices is analogous to those introduced by laws and regulations to clean up the environment. The total system is interactive and changes often prove to be counterproductive. Ample evidence of this phenomenon exists and some learning from past mistakes is needed.

Key factors that need consideration in developing a program to more effectively utilize energy fuels are:

1) The capital stock of energy consuming equipment is large and has been designed consistent with a historic price developed by the energy supply industry.
2) Many energy fuels are intersubstitutable in many applications even in the relatively short term. For example, natural gas and electricity in residential commercial sectors, and residual oil and coal or distillates and natural gas in industry and electric power generation. Pricing policies that do not consider interfuel shifts may only cause changes among fuels which may not be the objective of a resource conservation program.
3) Anticipating future energy pricing is a key segment of effective energy planning and consumer decisions. Because of long lead times for changes in capital stocks and also the long lifetimes of these stocks any changes from past trends in energy availability or price must be well communicated to consuming sectors.

For example, the automobile has one of the shortest effective lifetimes, approximately 10 years. The time for design and production changes, however, adds another decade to make the effective lifetimes for change as much as two decades.

4) The design of energy consuming equipment is often effectively insulated from market prices of fuels. For example, the home construction industries, consumer durables, commercial rental space, and urban growth stimulated by highway design are all influenced more by social factors, industry structure, and short run costs of capital than energy markets.

5) The establishment of environmental criteria and regulations to control air and water quality are separated from the energy market. Thermal additions to water bodies, SO_2 emissions from combustion facilities, and auto emissions all have a first order influence on energy utilization.

6) Energy demand and consumption is not controlled by a single large macro-economic market but has very fine structure by region and user. There are even marked differences among plants of the same general type depending upon the mix of of output products or services performed and the quality of the resource inputs. Energy use decisions are required which involve very fine structure even for micro-economic analysis. Technology and economics are closely intertwined and require case by case decisions for optimal use of all natural and financial resources.

Considering the complexities involved in both the supplying and consuming industry and the need for energy analysis at a very disaggregated level it is very risky to establish broad policy guidelines for optimal energy resource utilization. Even so there does seem to be some guideline that one can infer from the present availability of energy resources coupled with historic pricing and use policies.

PROPOSED GUIDELINES

1. The optimal energy resource utilization for the U.S. will best be developed by a policy that eliminates all subsidies to energy fuels and that makes energy consuming equipment carry the full costs, social and environmental, for the function performed.

2. Energy subsidies by regulation or taxation should not be changed on a one shot basis but should be phased out in a sequential manner over times as long as a decade with steps that are accurately known by the consumers of energy, the manufacturers of energy consuming equipment and the suppliers of energy fuels.

3. Incentives to improve energy efficiency of capital stocks should accompany elimination of energy subsidies (item 2) whenever there is evidence that the market won't function properly or there are solid policy reasons for accelerating change for social or environmental reasons.

4. Changes in pricing patterns will impact some income groups more than others, particularly those in the lower income groups whose budgets include a large proportion for energy fuels. Some incentives of tax adjustments are needed during periods of rapid capital stock adjustments to increasing prices. Research projection of future energy fuel pricing is needed for consumers to adjust their energy consuming equipment and energy use priorities effectively.

5. Biases in favor of domestic energy supplies may be desired for security or economic reasons. When this is a goal the approach should involve taxes on competing energy supplies or other measures rather than subsidies which lower domestic prices below domestic costs.

Consumption of energy fuels based on the proposition that shortages are imminent is of doubtful validity. The use of energy resources based on their costs of discovery, production and distribution by an energy supply industry which is treated equally taxwise with all other industries should lead to wise resource utilization. The transition from highly distorted market pricing to ones reflecting all the costs will be difficult and cause all energy industries to make major shifts in traditional operating policies. Many arguments will be given that continuation of present priorities of resource subsidies is essential to guarantee the vast amount of capital needed for energy supplies. Such arguments will almost surely defeat any program of energy conservation based on the true value of energy resources. The above five guidelines will require difficult adjustments for both consumers and suppliers but not adjusting appears to carry with it even greater problems for the U.S. industrial society.

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(LECTURE NOTES FOR A SUMMER COURSE)

Appendix Paper No. 13

MIT Energy Laboratory

RESIDENTIAL AND COMMERCIAL ENERGY UTILIZATION

INTRODUCTION

As one looks at the problems of pollution and resource depletion which make energy use increasingly expensive, it is impossible to avoid looking at ways in which energy utilization can be improved. Energy utilization is a very large field. In these notes we shall restrict our attention to the residential and commercial sector. We will show what we are doing, what we could do with the application of existing technology and what the ultimate thermodynamic limits are for accomplishing the same ends which we now are.

CURRENT ENERGY UTILIZATION

A graphic representation of where our energy comes from, in what form it is used, and where it goes is displayed on Figure 1.* Here the importance of the industrial and residential and commercial sector can be seen. Approximately one quarter of the energy is used in the form of electricity while three quarters is used as heat. This is important because it points to a way of conserving energy by using the waste heat from electric power generation and industrial processes for heating and space conditioning needs.

We can also see, on Figure (1), the great variety of uses for this energy, with space heating as the only large use. This means improvements in utilization will not be accomplished in a stroke but only by the patient plugging of a lot of small leaks in the system which we now have.

Figure (1) does not show enough detail for one to see how the

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* Cook, Earl, "The Flow of Energy in an Industrial Society" Scientific American Vol. 224, No. 3, p. 135, September, 1971.

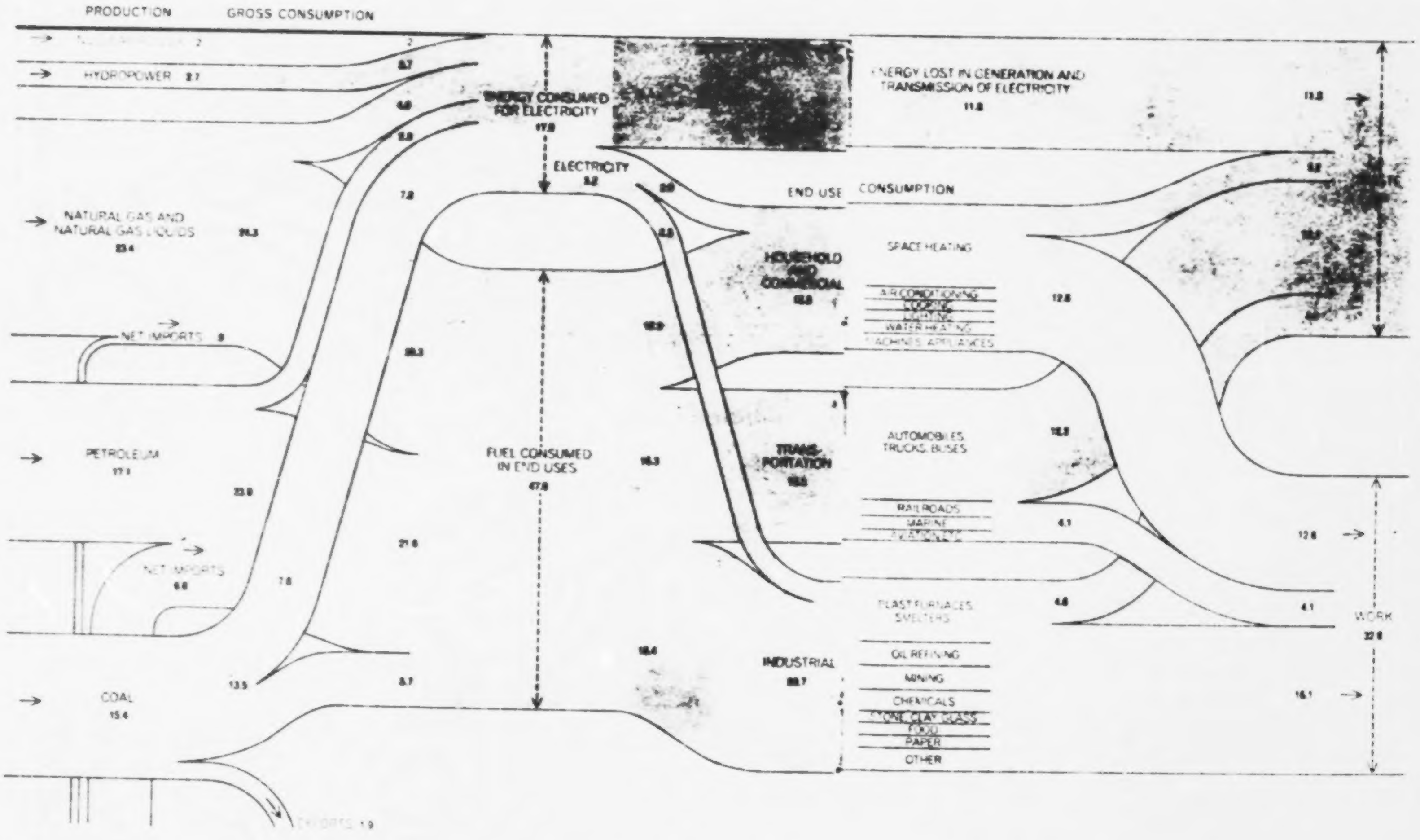
PRODUCTION
GROSS CONSUMPTION
2
HYDROPOWER 2.7
2
2.7
4.6
2.3
ENERGY CONSUMED FOR ELECTRICITY
17.9
ELECTRICITY
5.2
NATURAL GAS AND NATURAL GAS LIQUIDS
23.4
24.3
7.2
NET IMPORTS 9
20.3
PETROLEUM
17.1
23.0
FUEL CONSUMED IN END USES
47.8
21.6
NET IMPORTS
6.6
7.8
COAL
15.4
13.5
8.7
EXPORTS 1.9
2.0
2.2
19.9
16.3
19.4
ENERGY LOST IN GENERATION AND TRANSMISSION OF ELECTRICITY
11.8
END USE
CONSUMPTION
HOUSEHOLD AND COMMERCIAL
18.8
TRANSPORTATION
16.5
INDUSTRIAL
20.7
SPACE HEATING
AIR CONDITIONING
COOKING
LIGHTING
WATER HEATING
MACHINES, APPLIANCES
AUTOMOBILES TRUCKS, BUSES
RAILROADS
MARINE
AVIATION, ETC.
BLAST FURNACES SMELTERS
OIL REFINING
MINING
CHEMICALS
STONE, CLAY, GLASS
FOOD
PAPER
OTHER
12.6
12.2
4.1
4.6
11.8
12.6
4.1
16.1
WORK
32.8

Figure 1: The sources, transformations, uses and final form of energy as used in the USA in 1970. The units are BTU/year x 10^{-15} for all the numbers shown. (Reference 1)

minor uses for energy are divided up so Table (1)* is included. Here both the energy used to generate electricity and the energy used directly as heat are included in the total shown in the last column. Once again it is clear that the end uses are spread over a large number of small applications. If we turn our attention to only the residential and commercial applications, we can see that space heating is far the most important use. The lighting component, for instance, is included in the "other" category on Table I.

How well are we using this energy in the various devices which we are using to accomplish these ends? Reference (2) again gives some estimates. The estimates are reproduced on Table II. In this case the efficiencies referred to are the efficiencies compared to a similar, but thermodynamically perfect, device doing the same job. For instance, a heat pump would use less energy than a boiler to heat a home. This doesn't show on Table II, however. All that enters on Table II is the boiler efficiency, i.e. the fraction of the heating value of the fuel that ends up in the house. Though some of the efficiencies are low, the potential energy savings obtainable from simply improving these figures are not large enough to allow one to hope for a major improvement in energy utilization by simply improving appliance efficiencies. The system in which these devices operate must be changed too.

Another important factor we must keep in mind is the time scale for these changes. Typically a power plant is run for 30 or 40 years before replacement. It is very unlikely that an existing power plant would have a back fitted waste heat utilization scheme built on it. The commitment we make to a system now will last for 30 years. The home heating system has a similar lifetime. With such a long time scale, any changes will be long in working out. Decisions to change a system which are made now will not be completely implemented until 30 years from now.

Not only is the consumption of energy by use important but also the growth rate of each use. If we consider the various applications

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* "Patterns of Energy Consumption in the United States" Stanford Research Institute, January 1972.

Table I

ENERGY CONSUMPTION IN THE UNITED STATES BY END USE

1960-1968

(Trillions of Btu and Percent per Year)

Sector and End Use	Consumption 1960	Consumption 1968	Annual Rate of Growth	Percent of National Total 1960	Percent of National Total 1968
Residential					
Space heating	4,848	6,675	4.1%	11.3%	11.0%
Water heating	1,159	1,736	5.2	2.7	2.9
Cooking	556	637	1.7	1.3	1.1
Clothes drying	93	208	10.6	0.2	0.3
Refrigeration	369	692	8.2	0.9	1.1
Air conditioning	134	427	15.6	0.3	0.7
Other	809	1,241	5.5	1.9	2.1
Total	7,968	11,616	4.8	18.6	19.2
Commercial					
Space heating	3,111	4,182	3.8	7.2	6.9
Water heating	544	653	2.3	1.3	1.1
Cooking	98	139	4.5	0.2	0.2
Refrigeration	534	670	2.9	1.2	1.1
Air conditioning	576	1,113	8.6	1.3	1.8
Feedstock	734	984	3.7	1.7	1.6
Other	145	1,025	28.0	0.3	1.7
Total	5,742	8,766	5.4	13.2	14.4
Industrial					
Process steam	7,646	10,132	3.6	17.8	16.7
Electric drive	3,170	4,794	5.3	7.4	7.9
Electrolytic processes	486	705	4.8	1.1	1.2
Direct heat	5,550	6,929	2.8	12.9	11.5
Feed stock	1,370	2,202	6.1	3.2	3.6
Other	118	198	6.7	0.3	0.3
Total	18,340	24,960	3.9	42.7	41.2
Transportation					
Fuel	10,873	15,038	4.1	25.2	24.9
Raw Materials	141	146	0.4	0.3	0.3
Total	11,014	15,184	4.1	25.5	25.2
National Total	43,064	60,526	4.3	100.0%	100.0%

Note: Electric utility consumption has been allocated to each end use.

Source: Stanford Research Institute, using Bureau of Mines and other sources.

Reference 2

Table II

TECHNICAL EFFICIENCY OF ENERGY CONVERSION, BY END USE
(Percent)

	Coal	Natural Gas	Petroleum Products	Electricity
Residential				
Space heating	55%	75%	63%	95%
Water heating	15 *	64	50	92
Cooking	*	37	37 †	75
Clothes drying	*	47	47 †	57
Refrigeration	*	*	*	50
Air conditioning	*	30	*	50
Other	*	*	*	**
Commercial				
Space heating	70 ‡	77	76	95
Water heating	‡	64	50	92
Cooking	*	37	37 †	75
Refrigeration	*	*	*	50
Air conditioning	*	30	*	50
Other	*	††	*	††
Industrial				
Process steam production	70	64	68	*
Generation of electrical energy	88 §	88 §	88 §	*
Electric drive	*	*	*	90
Electrolytic process	*	*	*	**
Direct heat				
Other	*	††	††	††
Utility	37 ‡‡	34 ‡‡	36 ‡‡	*

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* Fuel shown is not commonly used for end use shown.

† LPG is the petroleum product assumed to be used for this purpose. Consequently the efficiency shown is the same as that for natural gas.

‡ It has been assumed that water heating and space heating are co-functions when coal is fired (per SRI).

§ The efficiency shown is based upon the assumption that electrical energy is a by-product of process steam production. Consequently, condenser losses, stack losses, etc., are assigned to process steam production.

** Indeterminate.

†† Since a multitude of uses are included, it is infeasible to produce an efficiency figure.

‡‡ A wide range of steam station efficiency prevails due to varying economic factors. The values shown are representative and show the difference between fuel on a relative basis.

Reference 2

we find wide variations in the growth rates for the different uses. Table III* shows this. It is evident that air-conditioning is an important use which is also growing very rapidly.

If we look at the whole field of residential and commercial energy utilization we see two distinct ways in which utilization can be improved.

1) We can reduce the demand for heat or power by better design of the buildings, devices or machines using these forms of energy.

2) We can use thermodynamically different systems, a system which approaches a limit of performance different from either the pure work producing (with Carnot limits) or the pure heat producing devices working devices which we now have. It is the second alternative which we wish to pursue here.

ENERGY EFFICIENT SYSTEMS

Typically, at this time in the country, the demands for home or commercial heat are supplied by fossil fuel heated boilers while the demands for power are supplied by electricity generated in plants which do not supply anything else. This is an unnecessarily inefficient system, in that the waste heat from the power generation could supply most or all of the needs for home heating. This could be done with only a very small penalty in thermodynamic performance for the combined system. Figure 2** shows this.

An integrated system distributing both heat and power is called a total energy system. We shall look at what total energy systems can do for us first.

If we generate our power using fuel cells rather than power cycles using a working fluid like water, we are able to by-pass the second law limits of the Carnot cycle. Approximately 40% of the heating value of a fuel is converted into power in a conventional modern steam power

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* Miller, A.J., "Use of Steam-Electric Power Plants to Provide Thermal Energy to Urban Areas" ORNL-HUD-14, January 1971.

** Beall, S.E. Jr. "Uses of Waste Heat" ASME Paper 70-WA/Ener-6.

Table III

GROWTH IN ENERGY CONSUMED, BY SECTOR AND END USE*
1960 and 1968
(Trillions of Btu)

	1960			1968			Average Annual Rate of Growth 1960-68 (percent)		
	Direct	Purchased Electrical Energy	Total	Direct	Purchased Electrical Energy	Total	Direct	Purchased Electrical Energy	Total
Residential									
Space heating	4,795	29	4,824	6,194	164	6,358	3.3%	24.0%	3.5%
Water heating	730	155	885	1,125	223	1,348	5.6	4.7	5.4
Cooking	360	71	431	412	78	490	1.7	1.2	1.6
Clothes drying	29	23	52	67	51	118	11.0	10.5	10.8
Refrigeration	nil	261	261	nil	354	354	n.a.	3.9	3.9
Air Conditioning	nil	26	26	nil	66	66	n.a.	12.3	12.3
Other	nil	177	177	nil	454	454	n.a.	12.5	12.5
Total	5,914	742	6,656	7,798	1,390	9,188	3.5	8.2	4.1
Commercial									
Space heating	3,272	nil	3,272	4,214	nil	4,214	3.2		3.2
Water heating	226	nil	226	371	nil	371	6.4		6.4
Cooking	27	23	50	61	79	140	10.7	16.7	13.7
Air conditioning	43	226	269	172	323	495	18.9	4.6	7.9
Feedstock	734	--	734	984	--	984	3.7		3.7
Other	nil	271	271	nil	677	677		12.1	12.1
Total	4,302	520	4,822	5,802	1,079	6,881	3.8	9.6	4.5
Industrial†									
Process steam	10,795			12,524			1.9		
Electricity generation	350			410			2.0		
Direct heat	2,210			4,212			8.4		
Feedstock	1,370			2,202			6.1		
Total	14,725	1,306	16,031	19,348	2,043	21,391	3.5	5.8	3.7
Electric utility	7,159	(2,586)	4,573	12,443	(4,530)	7,913	7.2	7.3	7.1
Transportation	10,964	18	10,982	15,136	18	15,154	4.1	--	4.1
Total	43,064	--	43,064	60,527		60,527	4.3		4.3

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* Not including heat wasted in production of electricity.

† Purchased electricity not allocated separately.

Source: Bureau of Mines, Stanford Research Institute

Reference 2

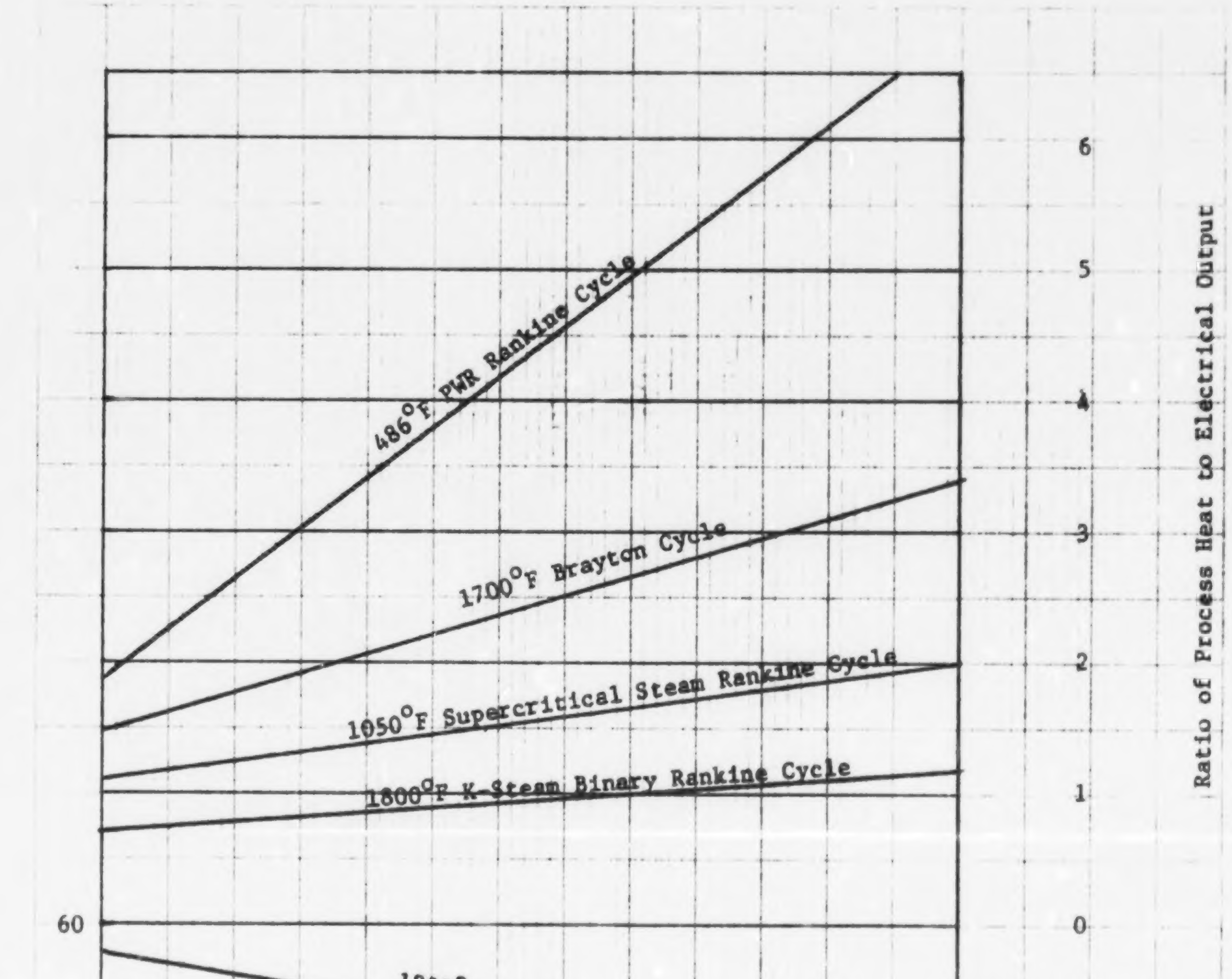

Figure 2: Effect of heat removal temperature on electric power generation

plant. If fuel cells are used which are run on a selected fuel like hydrogen, the efficiency of conversion of free energy, rather than enthalpy, for fuel cells can be as high as 80%. Fuel cells clearly have the potential to do a much better job than we are doing now.

If we go one step further, we can replace furances supplying heat by heat pumps and an additional savings is possible.

In what follows, we shall look at the thermodynamic potential for each of these alternatives assuming that:

1) Heat and power can be stored for any length of time in any amount.
2) There are no conversion losses, i.e. the machines are thermodynamically perfect.
3) Heat transfer can be accomplished with negligible temperature differences.

Consider, for example, a small house using oil for heat, gas for cooking and hot water, and electricity for lighting and small appliances. The fuel demands for the house are the following:

TABLE IV

Utility Consumption for a Small House

Oil - 100 gas/month	or	14×10^6 BTU/mo
Gas - 3000 ft^3/month	or	3×10^6 BTU/mo
Electricity	or	1×10^6 BTU/mo
	TOTAL:	18×10^6 BTU/mo

In order to provide electricity at a rate equivalent to 1×10^6 BTU/mo, it is necessary to burn fuel with a heating value of approximately 4×10^6 BTU/month, because of losses in generation, transmission, and distribution. The total fuel consumption is as follows: Total for separate heat and work systems = 21×10^6 BTU/month.

Now let us consider what we could do if waste heat were used for heating. Let us assume that 1/3 of the gas is used for cooking and 2/3 is used for hot water, and all of the oil is used for space heating. The net heat (hot water and space heating) demand is then 16×10^6

BTU/mo while electricity demand is 2×10^6 BTU/month. The ratio of these two is such that a very inefficient prime mover could be used to provide all the electric power and have sufficient waste heat left over for all heat needs. If we adopt this system, the total fuel consumption will be as in Table V.

TABLE V

Improved Total Energy System Energy Consumption

Electricity	2×10^6 BTU/mo
Heat	16×10^6 BTU/mo
TOTAL:	18×10^6 BTU/mo

So a real savings is possible. This is the savings possible if we go to a total energy system with waste heat utilization of some form.

Now let us look at the fuel consumption with the ultimate system, fuel cells for power generation, and heat pumps for heating. In order to evaluate this system it is necessary to specify the temperature at which the heat is to be supplied. Let us choose a temperature of 150° F for the heat and an outside temperature of 30° F (average for a heating season).

A heat pump operating between the outside at 30° F and the need at 150° F has a coefficient of performance of

$$\mathrm{COP} = \frac{\text{Useful heat}}{\text{Work}} = \frac{T_1}{T_1 - T_2} = \frac{610}{120} = 5.1$$

So the total power which must be supplied is as shown in the right hand column of Table VI.

TABLE VI

Demand			with heat pumps
Electricity	2×10^6 BTU/mo	=	2×10^6 BTU/mo
Electricity for Heat	$16 \times 10^6/(5.1)$	=	3.1×10^6 BTU/mo
TOTAL:			5.1×10^6 BTU/mo

Now the process used to convert chemical energy to electric power in a fuel cell is fundamentally very different from that which is used in a power plant. It is the free energy change from fuel to products rather than the enthalpy change which counts. In order to compare this all electric-fuel cell system with one which uses the fuel's heating value it is necessary to choose a fuel. Let us choose n-octane C_8H_{18} as the fuel. For this fuel it happens that the difference between the free energy and the enthalpy change as the fuel is reacted to carbon dioxide and water is negligible so we can calculate the fuel demands for these needs quite simply. This also means the heat interaction with the environment is negligible. For octane at 298° K the respective enthalpy and free energy changes in going from oxygen and octane to carbon dioxide and water vapor are:

ΔH = -19,029 BTU/lb of Octane (Enthalpy Change)

ΔG = -19,300 BTU/lb of Octane (Free Energy Change)

When these values are converted into equivalent fuel consumptions the results are as shown in Table VII.

TABLE VII

Equivalent Fuel Demands for Three Types of Systems for Small House

Heat and Electricity Independently Supplied	1,100 lb CH_4/month
Waste Heat Utilization	945 lb/month
Fuel Cell-Heat Pump	262 lb/month

It is clear that the advantages of going to a total energy system are appreciable and to a fuel cell system are very considerable.

Let us discuss the alternatives a little further. Any total energy system organized on a single home basis does not look very attractive. The total demands for heat and electricity are not very well balanced. If a more diverse load (including industrial and transportation) and a variety of heat and power sources are involved, the potential for savings is greater. About 30% of the fuel can be saved instead of the 15% shown in the first two alternatives of Table VII. The same potential is there if the appliances are changed so that the heat and power loads are balanced. Given the potential of fuel economies of 15 to 30% for systems using waste heat and 75% for systems using fuel also - what are the problems which prevent adoption of these systems now?

PROBLEMS WITH ENERGY EFFICIENT SYSTEMS

Reference (3) is a recent study of a total energy system for a city at the latitude of Philadelphia. It is a new city of 200,000 people. Costs were found to be marginally higher for the utilization of waste heat rather than those using entirely separate furnaces and power systems. No benefits for reduced pollution or the reduced fuel consumption (aside from cost) were taken however. It was found with an urban total energy system, heat cost $1.98 to $1.81/10^6 BTU while one burning fossil fuel to produce the heat needed gave costs of $1.70/10^6 BTU.

Let's now take a look at the problems which arise with energy efficient systems which make the cost advantages small. The first problem arises from the fact that the loads for heat and power are not in phase. Figures (3) through (9)* show how the daily and seasonal loads vary for heat and electricity. The steam demands for the summer are much lower than in the winter while the steam demand tends to peak in the morning while the power demand peaks at night. At this time there is no satisfactory way for storing either the heat or the power so that the importance of daily phase differences in demand can be reduced. Obviously if daily phase differences between heat and work cannot be reduced, yearly swings cannot either. In essence this means one must have substantial excess capacity for most of the year for both heat and power. It is the large investment in a lightly utilized heat distribution system which hurts the total energy system economics.

When one turns to the problems associated with specific pieces of equipment, other difficulties arise. Let us focus first on heat pumps.

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* Miller, A.J., "Use of Steam-Electric Power Plants to Provide Thermal Energy to Urban Areas" ORNL-HUD-14, January 1971.

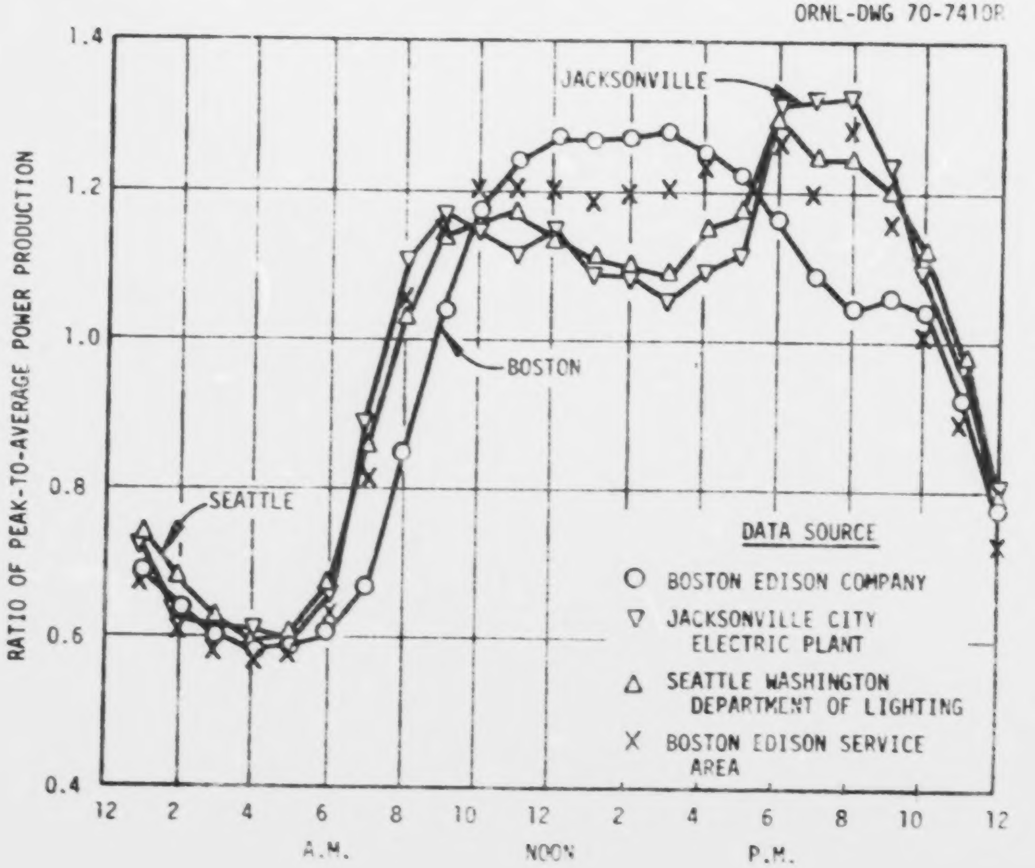

Fig. 3: Variations in the Electrical Loads of the Three Representative Cities on December 7, 1967.

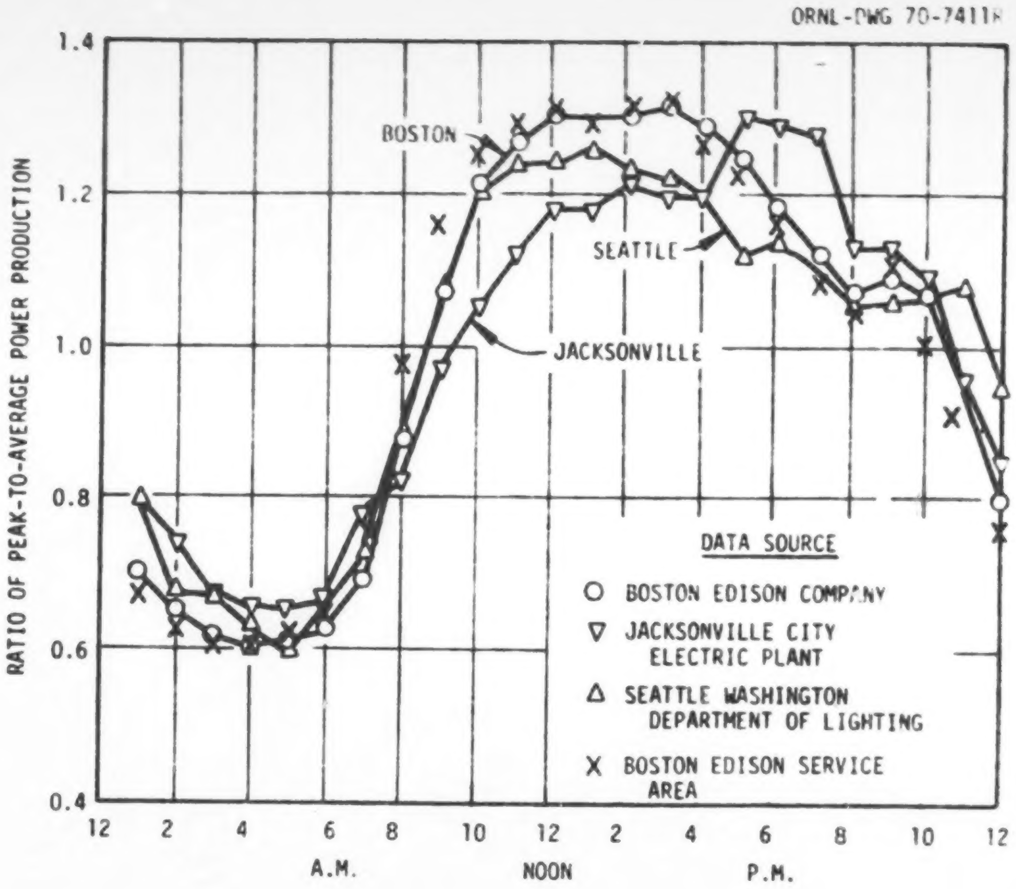

Fig. 4: Variations of the Electrical Loads of the Three Representative Cities on August 10, 1967.

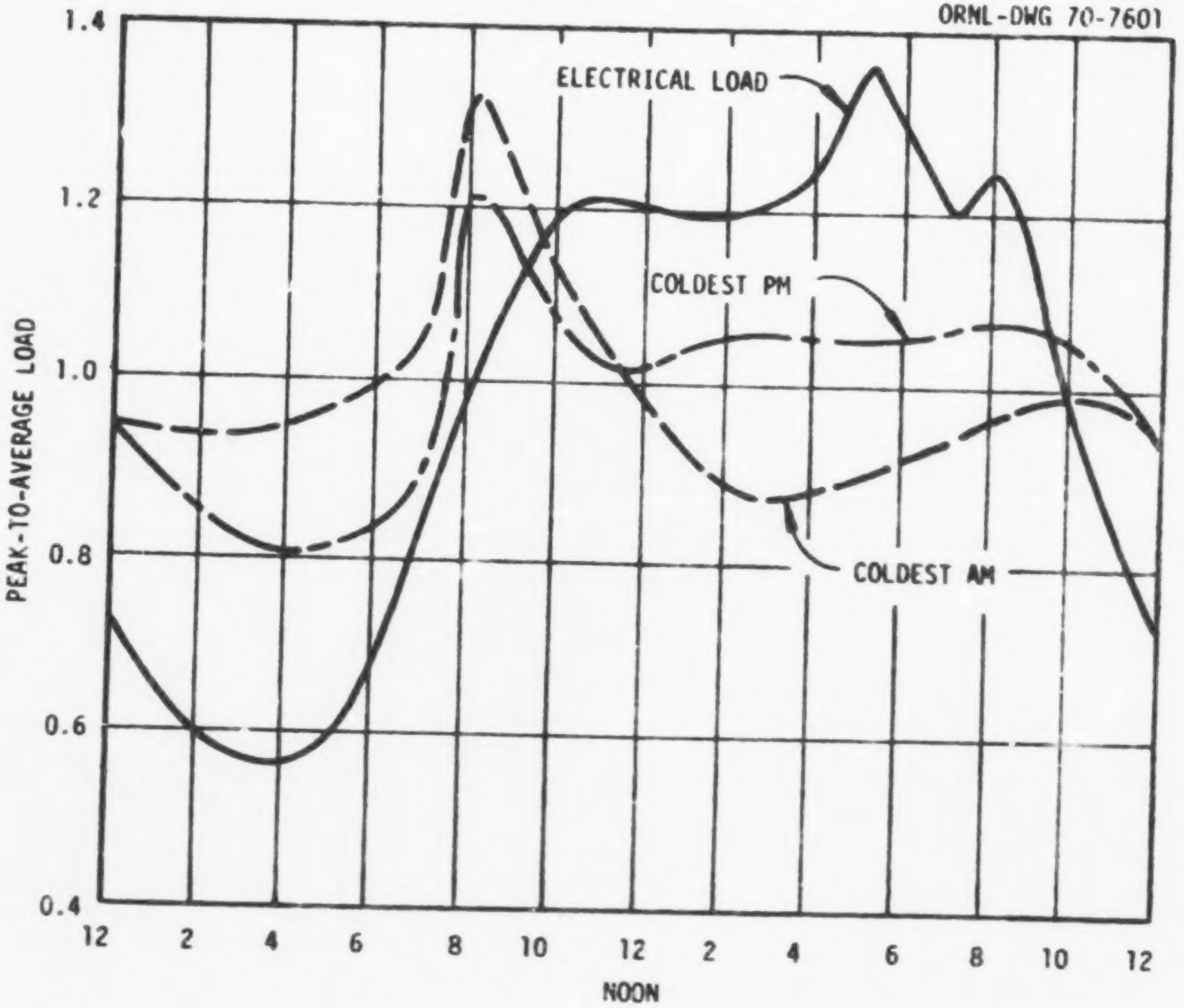

Fig. 5: Variations in the Diurnal Electrical and Heating Load.

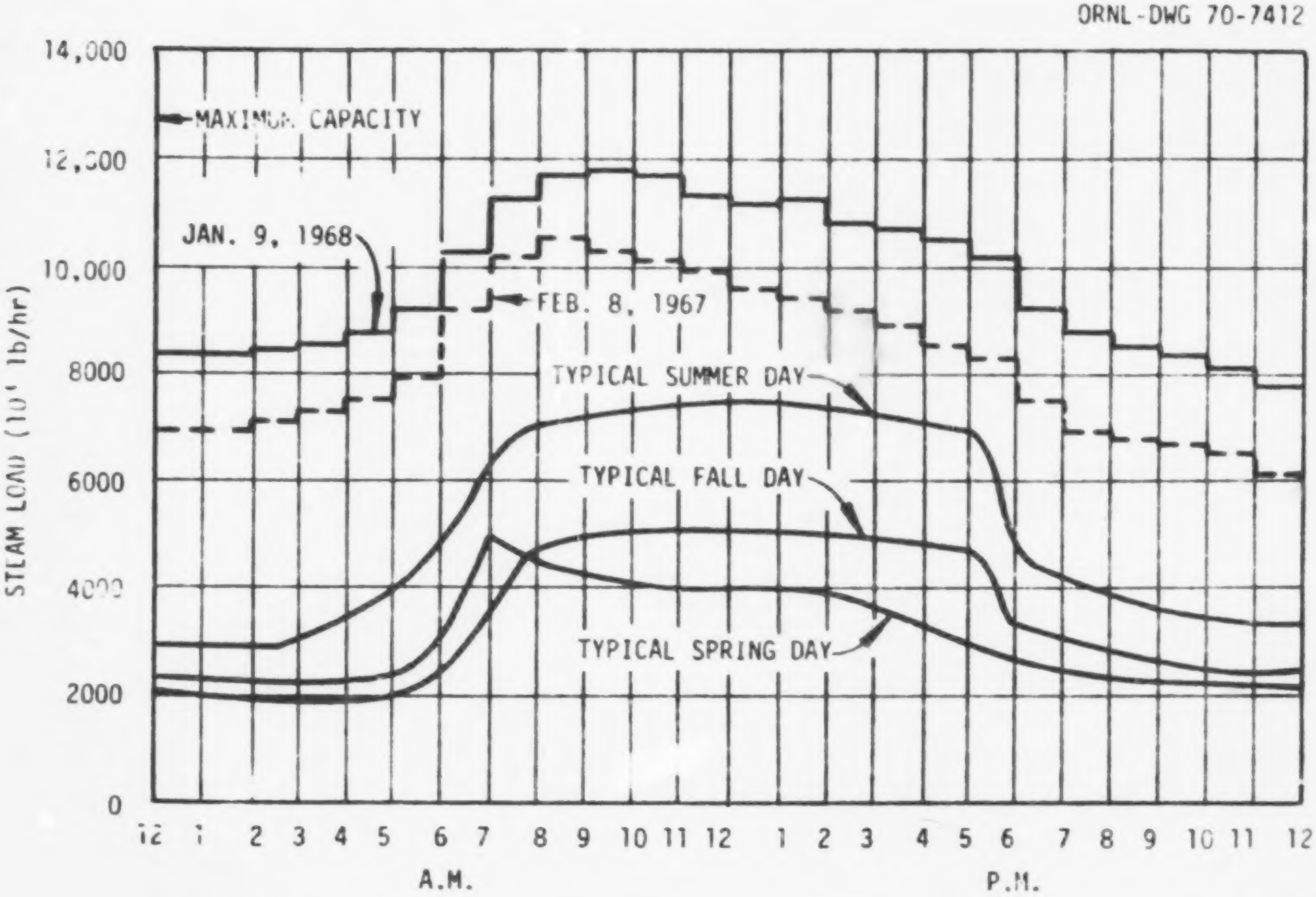

Fig. 6: New York Steam System Load Curves on Typical Days. (Information supplied by Consolidated Edison Company of New York)

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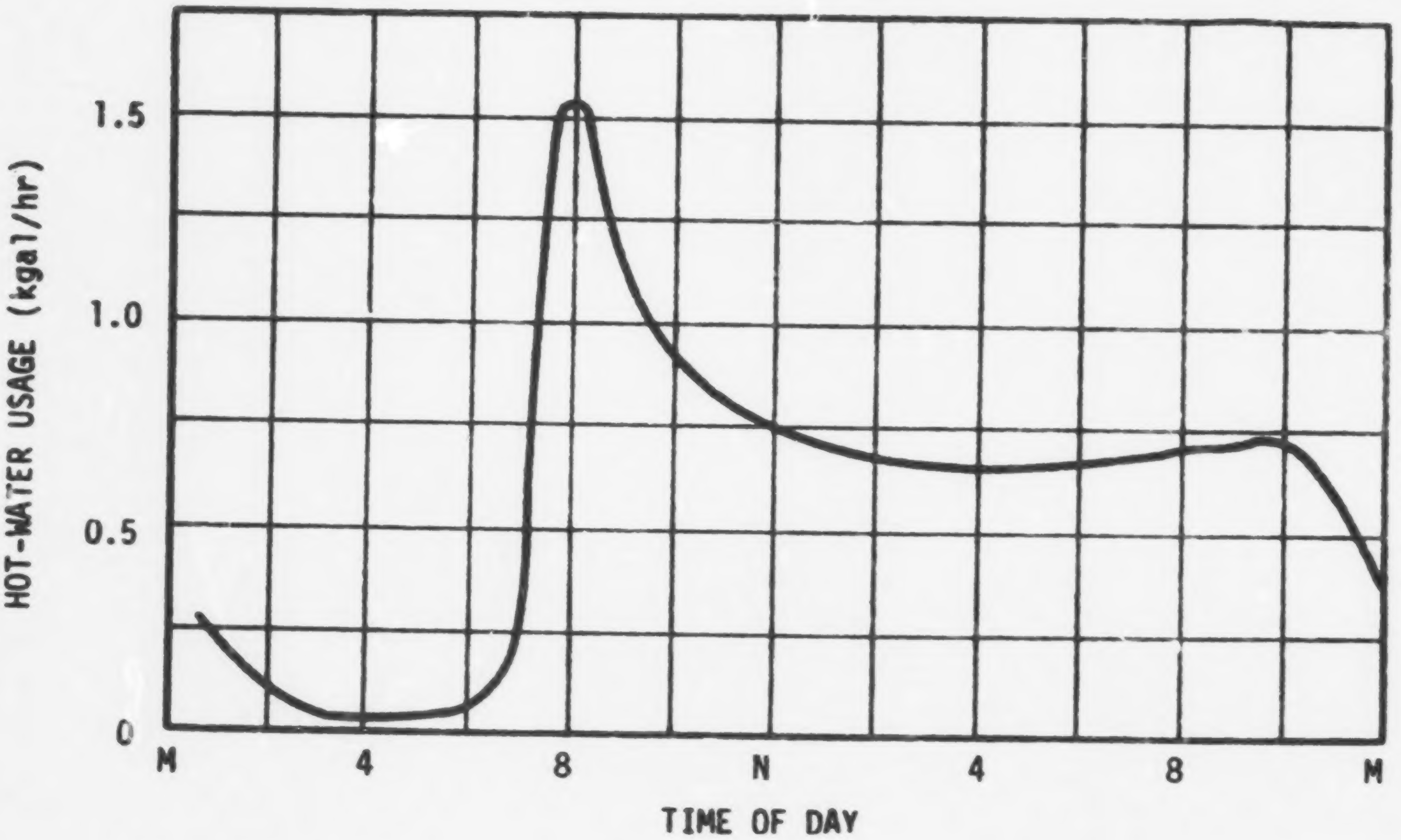

Fig. 7: Domestic Hot-Water Usage for Maximum Day.

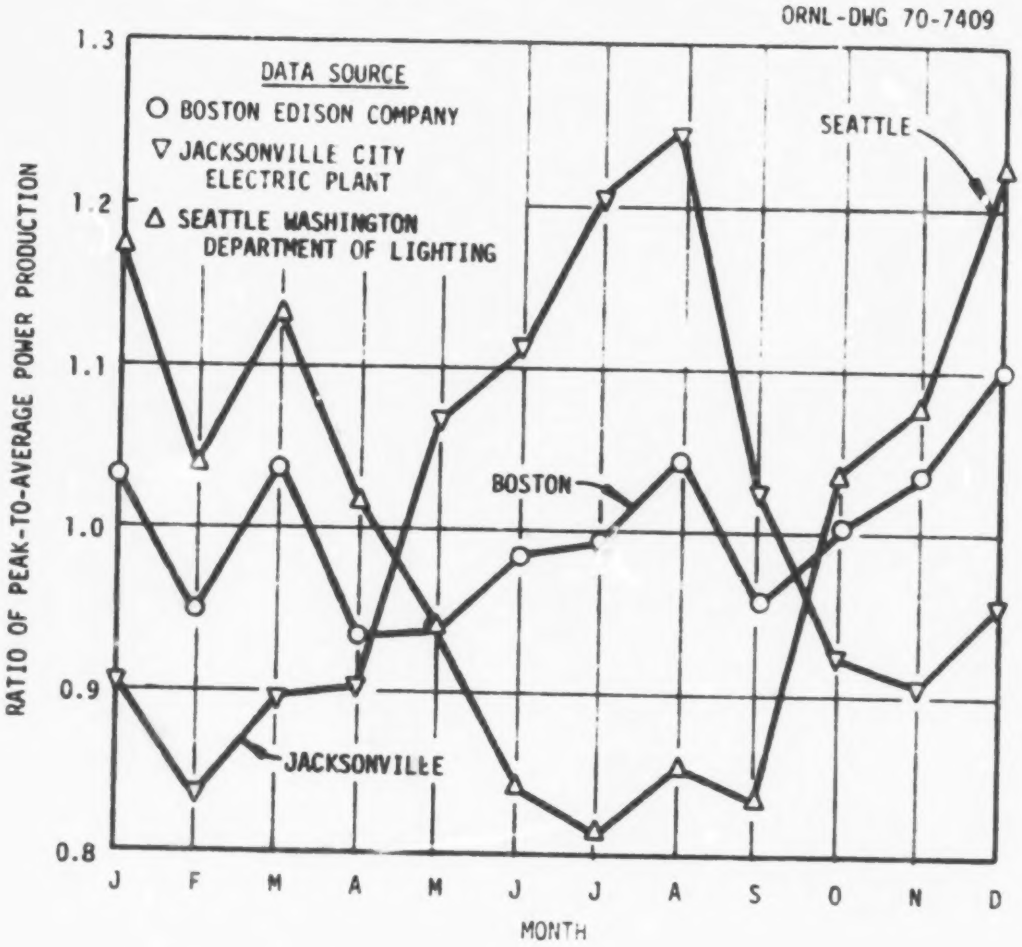

Fig. 8: Monthly Variations in the Electrical Loads of Three Representative Cities in the Year 1967.

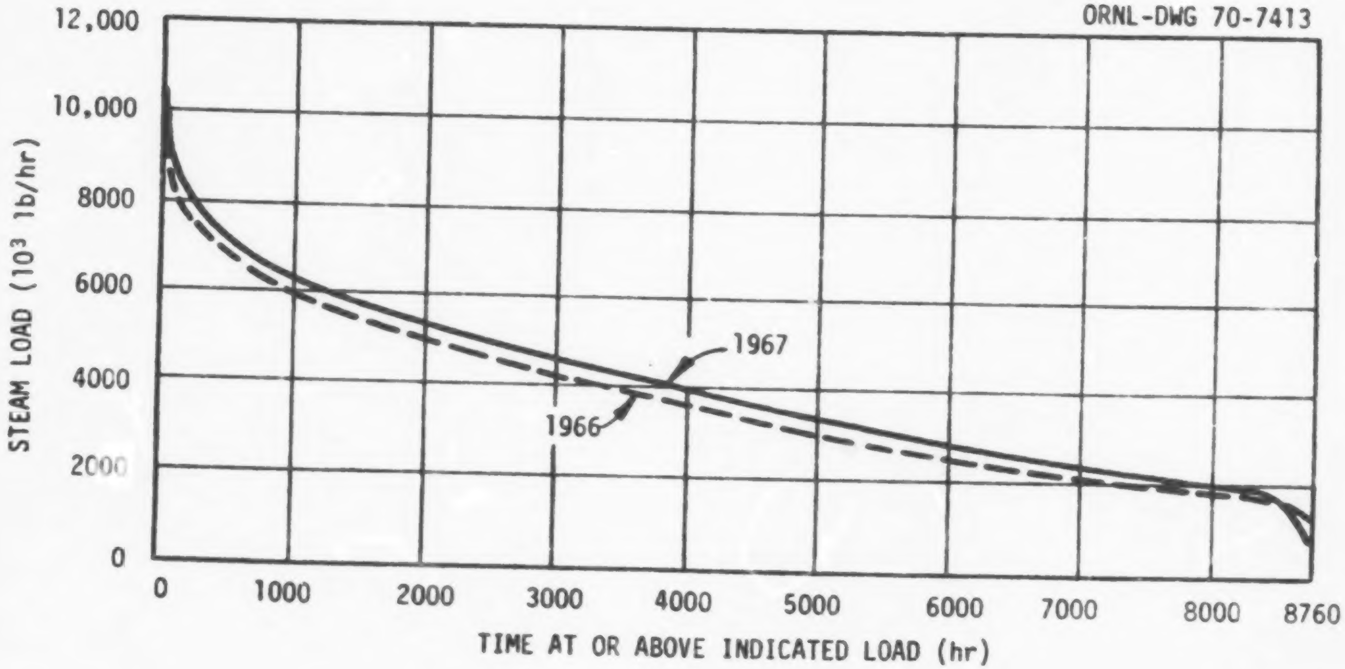

Fig. 9: New York Steam System Loads for Calendar Years 1966 and 1967. (Information supplied by Consolidated Edison Company of New York)

These are now stock items manufactured by all the major air conditioning equipment manufacturers. Most of them have about the same rated capacity as air conditioners as they have as heat pumps. Typically they reject heat to the atmosphere when operating as air conditioners and take heat from the atmosphere when operating as heat pumps. It is the air heat exchangers in these devices which cause most of the problems.

When one tries to remove heat from the air, for high air temperatures, condensation occurs. This is not harmful. However, as the temperature drops, the heat transfer surfaces drops below the freezing temperature and freezing occurs on the coils. The frost seriously reduces the heat transfer and impedes the air flow so that periodic defrosting is necessary. The heat to defrost reduces the amount of useful heat available while the defrosting time reduces the availability of the unit. More than any other factor, the air heat exchanger makes a heat pump an unattractive device.

The heat pump also has a poor characteristic as the temperature range over which it works is increased. Figure (10)* shows this characteristic. Boilers don't have this characteristic in that the amount of heat released per pound of fuel burned is virtually independent of the outside temperature. With a heat pump, the coefficient performance drops steadily as the outside temperature drops. This means either supplementary electric heat and/or substantial excess capacity must be provided in the system.

Another type of heat pump is possible which would go quite a way toward stretching fuel used for heating. This pump would use an adsorption refrigeration cycle as the working part. It would appear that such a heat pump would release to the house about twice the amount of heat which was contained in the fuel burned. The extra heat would still have to come from the air, however, so that the air heat exchanger problem is not [illegible]nated.

The most important device which is needed in developing energy efficient systems is the fuel cell. More than any other device, the

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* Mark's Standard Handbook for Mechanical Engineers McGraw-Hill Book Co., 7th Edition, pp. 12-119, 1967.

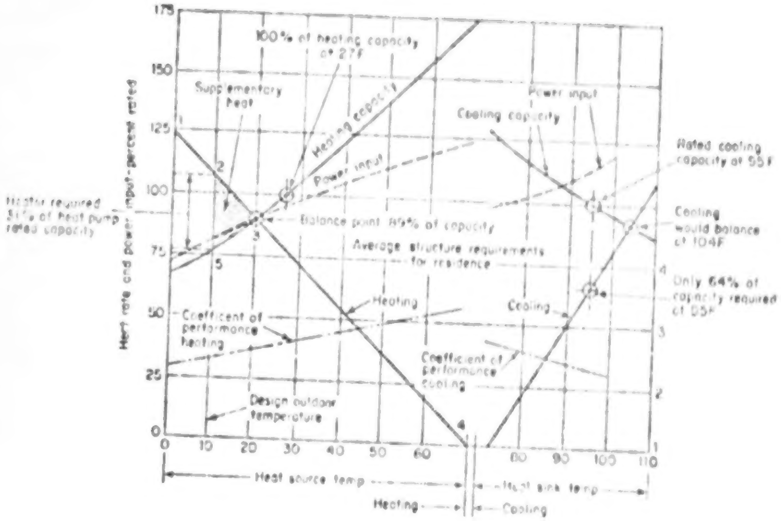

Figure 10: Operating characteristics of single-stage unmodulated heat pump-air source, air condensing. NOTE: Power input is at capacity. Reference 4.

fuel cell meets the two problems of fuel depletion and environmental pollution. Let us take some time here to discuss the fuel cell in the context of the energy problems of the near and more distant future.

Fuel cells are batteries which run on electrodes which catalyze the reaction of the fuel. Instead of replacing the battery (or electrode) one replaces the fuel which is consumed as the reaction proceeds on the electrode. This device avoids the combined 2nd law - materials temperature limit which restricts prime movers now in operation to about 40% thermal efficiency. The fuel cell approaches a conversion efficiency of 100% (based on free energy). Free energy efficiencies of 70% are attainable now on oxygen-hydrogen fuel cells with platinum electrodes. Depending on the fuel, the free energy change or reaction can be greater or smaller than the heating value but is usually about the same size. Why, now, is such an attractive device so little in evidence?

The essential problem is finding an electrolyte and an electrode material which catalyzes the fuel adequately. The material must be reasonably cheap, have a high rate of reaction, and be difficult to poison. A satisfactory answer to all these problems has not been found. A more comprehensive hydrogen energy system must have fuel cells because no other device using hydrogen is economical enough to use such an expensive fuel. It is inconceivable that a 30% efficient heat engine used to generate hydrogen would be attractive if only 30% of the heat energy in the hydrogen were used for work subsequently. Overall efficiencies of 10% would result.

BARRIERS TO THE ADOPTION OF ENERGY EFFICIENT SYSTEMS

Power plants constructed in the Soviet Union are sited and designed on the assumption that the waste heat will be used for space heating. Most of the cities and all of the new construction work in the Soviet Union is built to use some kind of total energy system. The same is true of Sweden, and probably for the same reason. That is, the government controls utilities and the number of government bodies and review boards which must be consulted before making a change is small enough so change is possible.

With the more random growth and the older cities which characterize this country, the problem is somewhat different. The investment which must be made to install a total energy system is very large while the period of time over which development occurs is so long that it rarely pays for someone to do it at the outset, when it is easiest. An extreme case of slow motion redevelopment is the West-End here in Boston.

When I came to Boston in 1952, demolition had just begun at the West-End. Three years later demolition was complete. Ten years later construction was begun on the new buildings. Reconstruction now appears to be about 60% complete. An integrated total energy system for this complex would have required an initial investment which would erase most of the advantages of the system. A serious need is a total energy system which is flexible enough to grow with the demands of the system yet does not require a huge investment right at the start.

Another factor that strikes one on reading the history of a variety of total energy systems in the country is the number which are shut down a few years after being installed. Usually this is a result of negotiating some better rates with the local electric utility. The regularity with which this occurs makes one wonder if there isn't a better way of organizing things. Let's take a moment to explore these questions.

If we wish to construct an energy efficient system, the true cost of the energy must be reflected in the prices for heat or electricity and institutional barriers to its effective utilization must be removed. As the utility industry is now regulated, returns are limited to a fixed percentage of investment so that the only way to increase returns to the utility is to increase systems size and electricity consumption - primarily off peak consumption. Do we really want to increase electricity consumption? At this time the waste heat is a bother and current power plant siting practice places the power plants as remotely from the city as possible. This almost precludes efficient utilization of waste heat. Furthermore, the cost of putting in district heat, generally using waste heat from a power plant, means that only a few old cities in the United States (built before fuel became too cheap) have such systems. These systems were installed before the competing oil and gas systems were developed. If a single utility provided combined power and heat services I expect a very different system from the one which we now have would have evolved. Those countries with different institutional arrangements have evolved a different system. So part of what we see here is due to modes of organization typical of this country.

NEEDED WORK

The most pressing need is the description of a system in which the economic interests of the various sectors in the energy economy and the best interests of society can be made to coincide. To find such institutional arrangements first the best system will have to be identified so that the barriers to its adoption can be found.

Several technical areas need work. Top among these is the fuel cell. A cheap, reliable fuel cell electrode for hydrogen air reactions is badly needed as this is the only device which shows promise of reducing both the energy demand and pollution from energy use or conversion. Of comparable importance would be the development of a strategy for threading pipe through existing streets without digging up everything. This would allow back fitting for an old city. Perhaps a special tunneling machine would do the job.

The adoption of heat pumps, i.e. their adaptation to conventional systems, depends on the development of a satisfactory air heat exchanger; one which will not ice up, or occupy too much volume. This is also a need. The potential for efficient energy utilization in this country is scarcely scratched.

REFERENCES

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Working Paper No. 14

MIT Energy Laboratory

SYNTHETIC FUELS

Introduction

This is an attempt to take a look at the economics of synthetic fuels, and, in particular, coal gasification. The object of this exercise is two-fold. In the first place we attempt to put together the most recent information available on gasification costs. In the second place we present a crude evaluation of this technology, in an attempt to begin to focus in on the relevant questions such an evaluation should deal with.

In doing this evaluation we try to allow for technological changes that can take place between now and that point sometime in the future when gasification might be a working technology. In an effort to prevent this from becoming too speculative, we take a very restricted view of new technologies and limit ourselves to proven technologies that directly compete with synthetic gas. Previous discussion of synthetic gas has not adequately considered substitute technologies.

The argument is often made that because of the long lead times involved in the construction of these plants, it will be a while before they make a dent in U.S. energy consumption. The following discussion indicates that there might be more serious problems with the economic viability of some of these techniques.

Our view is a long-run view in the sense that we allow for changes in the energy-using capital stock. Given the time-delays that are anticipated for the introduction of synthetic fuels, it appeared this was the reasonable course. However, it does leave a gap in the evaluation that we mention later on, and could be the basis for future work.

We begin by briefly considering feedstock costs. We then go on to develop the costs for gasifying coal under various scenarios. Finally, we attempt to consider the costs of substitute technologies in an effort to get a handle on the problem of the economic viability of this particular technology.

Feedstock Costs

At present, the coal market is subject to chaotic conditions stemming from the large increases in oil prices. Spot coal prices have consequently reached historically high levels. However, long-run contract prices are lower and represent, for our purposes, the relevant price.

We take a price of \$.15 per million Btu for low-sulfur western coal at the mine-mouth. This is supported by recently signed contracts for this coal as well as engineering cost estimates. The other source of coal for midwestern plants would be the coal fields of Illinois, Indiana and West Kentucky. The price of coal at the mine mouth varies with the sulfur content of the coal. The relationship between price and sulfur content is non-linear, leading to steeply rising prices as the sulfur level goes below 2%. According to estimation we have done in previous work, the price of coal with 4% sulfur was 29¢ per million Btu at the mine-mouth as of the middle of last year. Prices have risen somewhat since then, and on a long-term basis are somewhat higher. In order to bias the case toward synthesis we use the lower price, although the effect is minor. In the long-run, the elasticity of supply of western low-sulfur and midwestern high sulfur coal is such that depletion should not lead to steeply rising coal costs. However, shifts in the supply function could be significant as wages increase, driving up the cost of underground mining. Restrictions on strip mining will do the same for surface mining.

Transportation costs for coal are greater than pipeline costs for gas, meaning that mine-mouth plants are preferred. This is the case even if water must be shipped to the plant. The combined cost of pipelining water to western plants and pipelining gas east to Chicago should be about 41¢ per million Btu. This must be compared to, at a minimum, 36¢ to deliver coal to eastern plants. The true cost is higher because the thermal efficiency of the gasification plants implies that at least 30% of the heat value is lost, meaning that a delivered cost of 36¢ is an effective cost of 51¢.

Synthetic Costs

With these feedstock and transport costs we can sketch out the costs in 1973 dollars of producing coal-based synthetics. At present, the technology for coal-based liquids is not developed. Those cost figures available indicate that shale oil will be a lower-cost source of liquid hydrocarbons and produces a higher-quality product. It is likely that without basic advance in coal-based synthetics, shale oil would preclude the development of present liquifaction technologies. We have therefore concentrated on gaseous fuels from coal.

In Table 1 we present the costs of producing synthetic high-Btu gas from coal. Tables 2-4 are alternative calculations as explained in the tables. There are several possible scenarios with either western coal being used as a feedstock and the gas shipped to Chicago, or midwestern coal used as the feedstock. In addition, we allow for costs of pipelining water from the Mississippi if necessary.

It appears that gasification is not necessarily a western phenomenon. The initial plants that can use local water supplies will find a cost advantage in the West. However, if production were to expand, water would have to be pipelined in from the Midwest, increasing the costs of the gas.Costs of all these alternatives are roughly the same. This situation could change if the price of midwestern coal were to escalate more rapidly than Western coal conferring an advantage on Western locations. This would occur if rising wages cause underground mining costs to escalate more rapidly than surface mining costs since the midwestern coal industry will have to rely more upon underground mining.

We have also allowed for a different stream factor, that is the percentage of the time that the plant is actually in operation. The lower figure of .7 is closer to that realized today by plants employing complicated chemical processes after years of experience.

We have also estimated probable gains from technological efficiency. Since so much of the cost is construction cost , there is little possibility for significant lowering of cost with these technologies. We have allowed for a 26 percent increase in thermal efficiency to a level of 83% and a 10% decrease in capital costs. The reader can use Table 1 to substitute his own hypothesis. It can be seen that these allowances make little difference in the cost, and the prospect for major advance with this technology is limited.

Evaluation

We can assess this technology in a crude way by comparing it to alternative fuels. However, the evaluation must take into account several factors. Because of the long lead time involved with these plants our evaluation must be long-term. We should allow for some changes in the capital stock of energy users. We must also allow,as stated at the outset,for technological developments that can be anticipated between now and the time in the early 1980's when these gasification plants might be ready.

Advantages of gasification that must also be accounted for in the evaluation are the low emission levels of the fuel at the point of use and the fact that it uses a domestic fuel and thus can contribute to the realization of greater independence for the United States from imported fuels. The low-pollution at point of use is not a total net gain with this fuel since it does involve the pollution associated with coal mining, either surface or underground. However, in order to present a more favorable case for synthetics, this is ignored. Furthermore, many of the alternatives to this fuel involve similar sources of pollution at the point of manufacture.

To deal with the independence aspect we also restrict our attention to domestic sources of energy. We therefore are not in a position to evaluate the trade-offs involved in basing greater independence upon synthetics. However, this allows us to present the most favorable case for synthetics.

There are two main areas in which gas can compete. We ignore the transportation sector and assume that only liquid fuels will be used in that sector. We are left with the residential and commercial, the industrial, and the electrical generation sectors. In broad terms, there are two alternative uses for this fuel:for bulk heat in industrial and electrical generation uses and those uses in the residential and commercial and the industrial sector where the cleanliness and ease of handling associated with gas are highly valued. These characteristics are particularly important in space heating and it is here that gas will have its highest utility.

The case for using gasified coal in bulk heating such as the electrical sector revolves around its low-pollution level. In this sense it can be viewed as a desulfurizer and an evaluation of the techniques can be made by comparing it to other forms of desulfurization.

There are three primary ways of desulfurizing coal. One is to burn low-sulfur coal. However, indications are that the supply of low sulfur coal in the East is quite inelastic. There have been large real increases recently in the long-run price of this high-quality coal and sizeable expansion of low-sulfur coal production in the East would likely drive the price quite a bit higher, although it is impossible to say how high. This rise would be limited by the ability of utilities to purchase Western low-sulfur coal. There are also alternative technologies in the form of low-Btu gas and stack-gas desulfurization. The costs of low-Btu processes are presented in Tables 2-4.

There is currently a great deal of controversy as to the reliability and cost of stack-gas desulfurization devices. In the span of years we must consider when dealing with synthetics, however, it is not unreasonable to assume that the devices will be perfected. We use as the cost of this technique, the highest published figure we have been able to find, 80¢ per million Btu from a Commonwealth Edison Company report. Together with a delivered cost of high sulfur coal of 45¢ (30¢ for coal & 15¢ transport), this is $1.25 per million Btu.

There is less controversy about the workability of low-Btu gasification. These costs, while higher than those for stack-gas desulfurization, still are lower than the high-Btu gasification costs when compared as a source of fuel for large industrial boilers. Furthermore factors that will cause escalation is these alternatives will have the same impact on high-Btu gasification since the components of cost are roughly the same.

The case for gasification therefore must be based on its use in processes where its cleanliness and handling ease are highly valued. This class of service must surely include some industrial uses; however, in a broad look such as this it is impossible to isolate those processes. Rather, we deal with a major non-industrial use - space heating. If gasification is not economically viable in this use, its usefulness is likely to be much more limited than has been anticipated. We use electricity as a standard here since if we can show that electricity, generated by nuclear power or coal, will be a cost-competitive substitute in space heating, we eliminate one of the major possible uses of synthetic gas as uneconomic.

The supply of electricity is complex for it depends upon the age structure of plants, the type of plants, and the load characteristics as well as fuel and capital costs. A more complete analysis will have to take these factors into account. We can't accomplish this here, but rather we take, in a first attempt to, in fact, see if further work would be useful, an average cost of electricity of 3¢ per kWh distributed to ultimate consumers. This is higher than the average residential rate of 2.64¢/kWh for the U.S. in 1973-1974. However, this is the 1973 rate for consumers of Commonwealth Edison. We use this rate for several reasons. Commonwealth Edison uses more nuclear power than any other utility, which reflects what will likely become a more common mix of plants for other utilities. In addition, Commonwealth Edison has been purchasing low-sulfur coal to comply with Chicago clean-air regulations. This rate is actually on the high side since residences using electric heat have higher kilowatt consumption and therefore lower average rates.

The long-run marginal cost of producing electricity should be the average ost of generation for the set of plants that minimizes the cost of production, given load characteristics, etc. As these characteristics change, so will the marginal cost. We have not considered this aspect here, so these calculations must be viewed as illustrative.

We also must take into account technological improvements that have already been developed and can be improved upon in the next few years. Specifically, we allow for the introduction of heat pumps that change work (electricity) into heat.

The heat pump is not a new technology and has been in use since the 1950's; however, early heat pumps suffered from problems with reliability. This coupled with low gas costs precluded their introduction. The situation is fundamentally different with regard to a wholesale gas price of $2.00 per million Btu.

In Table 5 we present a comparison between space heating with a conventional gas furnace and a heat pump system, using efficiency levels obtained in operation today. The economics of the heat-pump are best in relatively warmer climates, so we present the case for both middle and northern U.S. where electricity is likely to be at its greatest disadvantage.

The second part of each case in the table allows for a 90% increase in gas boiler efficiencies and a 75% increase in heat pump efficiencies. Both numbers are considered quite feasible by engineers; however, it was considered unlikely that gas efficiency could go over 85% anywhere. At levels of efficiency currently attainable, the heat pump is preferred everywhere. At the higher levels of efficiency the heat pump appears, given the accuracy of this data, to be a close substitute even in northern climates, and certainly preferred as one moves south.

It must be pointed out that this comparison is heavily biased against the heat pump. The heat pump provides air-conditioning capacity at a low increment in capital cost, thereby narrowing or eliminating the capital cost advantage in those regions where air conditioning is a factor. This is also true for large commercial buildings where both air conditioning and heating must be provided. This is a substantial advantage for the heat pump.

The future evolution of costs will depend upon the relative escalation in capital and coal costs as well as how electricity is generated. A proper accounting for all factors would consider how rising costs affect the choice of plants for gasification and for electric generation; however, a simulation model is necessary for this task. For both of these energy sources there is a variation in the relative fuel and capital intensiveness of the production process. If coal costs rise more rapidly than capital costs, this will favor nuclear power plants and western coal plants, where coal cost is a smaller portion of total cost. Given the wide range in factor intensities, and given that electricity will still be generated by some mixture of coal and nuclear plants, as a first approximation it does not appear too erroneous to conclude that these processes will be affected in roughly the same degree by rising coal and capital costs. This area though is clearly one where simulation would help sort out possible scenarios.

There is one potentially serious exception to this argument. If the sulfur restrictions on fuels force utilities to use low-Btu gas or some other expensive form of desulfurization, then the cost of electricity can go very much higher without a corresponding increase in high-Btu gas costs made from eastern high-sulfur coal. Yet, there is serious doubt as to the supply of non-caking eastern coal suitable for present technologies. Full reliance on these coals could lead to much higher prices much as metallurgical coal has earned a high premium in the past. Furthermore, very high desulfurization costs will lead to more reliance on nuclear power for base load generation.

Pollution

There is, of course, the pollution problem associated with electricity. The emission of particulate matter and of sulfur oxides increase the social cost of electric heating; however, this problem is of the same order of magnitude as the pollution associated with gasification plants. In either case desulfurization devices as well as particulate removal systems must be used to reduce the pollution associated with the combustion of coal. They both imply large-scale mining of coal and therefore imply the same level of pollution at the source of manufacture.

These arguments are not offered as proof that space heating will be converted to electricity. Rather, all that is being argued is that if gas prices reach $2.00 per million Btu, in wide areas of the United States electricity would be the preferred fuel. This is not a prediction that this set of circumstances will occur.

This preference is also a long-run one. In cases where installed capacity is being used, it might make sense to use the higher-priced fuel since the incremental capital cost is not just the differential in capital costs between the two systems, but rather the entire cost of the heat pump. Existing gas systems, however, have much lower efficiencies making the operating cost differential larger. More work could be done on this question in a full-scale assessment of the technology.

Implications

We have seen that more recent information on gasification costs show this to be a very high cost form of energy. It will, at best, be used in the residential and commercial sectors where the characteristics of gas are highly valued. The above calculations suggest that when competing technologies are considered the economics of gasification are questionable even in these uses. This evaluation should be pursued, and it could be integrated with models of electricity supply now in progress at the Energy Laboratory as well as alternative strategies for satisfying energy demand. The results of the analysis here suggest that the main obstacle to the introduction of synthetics is not the time lag, but rather the poor economics of the presently available processes.

We have tried here to suggest that on its own terms there appears to be a limited market for high-Btu gas at $2.00 per million Btu. Even the $2.00 price might well prove to be optimistic. It would appear that funds expended on development of present technology offer little promise of significant pay-off. We are still in the stage with regard to coal based synthetics that requires basic research aimed at new approaches and technologies.

TABLE 1

Part A

Coal Gasification Costs

(Delivered in Chicago)

Case	Type of Coal	Water Available	Technological Improvements	Stream Factor	Total Cost
1	Western	Yes	No	.8	$1.90
2	Western	No	No	.8	$2.07
3	Western	No	Yes	.8	$1.89
4	Western	Yes	No	.7	$2.13
5	Western	No	Yes	.7	$2.11
6	Illinois	Yes	No	.8	$2.08
7	Illinois	Yes	Yes	.8	$1.86
8	Illinois	Yes	Yes	.7	$2.08

Source: See Part B

TABLE 1

Part B

Case	Coal Costs	Operating Costs	B.P. Credit	Cap Charges	Shipping	Total
1	.30	.465	-.252	1.15	.24	$1.90
2	.30	.632	-.252	1.15	.24	$2.07
3	.24	.632	-.252	1.03	.24	$1.89
4	.30	.53	-.252	1.31	.24	$2.13
5	.24	.697	-.252	1.18	.24	$2.11
6	.58	.50	-.252	1.19	.06	$2.08
7	.48	.50	-.252	1.07	.06	$1.86
8	.48	.57	-.252	1.22	.06	$2.08

Sources:

Exxon-EPA-1/60/3-74-009-b June 1974

1973 El Paso FPC Application

Plant size: 250 mmBtu day, (lhv)
Total Btu/year output: 73×10^6 mmBtu/yr, low heating value
Stream factor: .8
Coal cost derivation: $\frac{\text{Annual feed cost (\$)}}{\text{Annual output (mmBtu)}}$, evaluated at $.15/mmBtu for

Western Coal and $.29/mmBtu for 4% Sulfur Midwest Coal.

Operating costs include plant operation and contingency evaluated at 10% of the sum of annual plant operating cost and the cost of the coal feed. Where applicable $.167/mmBtu for water is added to the total. (Exxon EPA report)

By-product credit at $.75/mmBtu. (Exxon EPA report)
Cap. charges: calculated @ 21.5% of total investment, corresponding to 10% DCF. Allowance made for additional sulfur removal by assuming sulfur removal cost proportional to (% sulfur)$^{.5}$. (Exxon EPA report and conversation with J. Longwell)

Shipping @ $.03/mmBtu x 100 miles, Johnson, S.E. "Storage and Transportation of Synthetic Fuels", ORNL-TM-4307, ORNL, Sept. 1972.

Table 2

	Input fuel (tons/day)	Thermal Efficiency (per cent)	Total Capital[6] ($ million)	Annual Operating cost ($ millions)	Costs(cents per million B.t.u. of product)[8]			
					Capital[7]	Operating Costs[5]	Coal or Oil Shale Cost	Total Cost[9]
Coal gasification								
Lurgi-bituminous[1]	14,700-17,900	56-68	334-390	21.4-22.2	98.4-115	29.3-30.4	47.1-57.1	174.8-202.5
Lurgi-Western[2]	19,600-23,800	56-68	290-390	19.5-23.0	85.4-115	26.7-31.5	23.5-28.6	135.6-175.1
Coal liquefaction	13,200-17,500	60-75	233-373	22-35	68.6-110	30.1-48.0	42.7-53.3	141.4-211.3
Low-B.t.u. gas								
Bituminous[1]	12,500-14,300	70-80	195-208	16-18	57.4-61.3	22-24.7	40-45.7	119.4-131.7
Western[2]	16,700-19,000	70-80	195-208	16-18	57.4-61.3	22-24.7	20-22.9	99.4-108.9
Methanol-bituminous[1]	14,900	60-67	279-364	44	82.2-107	60	47.8-53.3	190.0-220.3
Oil shale								
Gasification	94,500	74	415	-	122	32.3	56.1	210.4
Liquefaction[3]	72,900	96	342-360	-	101-106	34.9	42.8-48.2	178.7-189.1
Liquefaction[4]	52,000	96	276-327	-	81.3-96.3	30.2	46.8-52.6	158.3-179.1

Plant Costs for 250 x 10^9 Btu per day of Various Synthetic Fuels.
Derived from May 1974 Technology Review Article.

[1] Thirty-two cents per million Btu, 25 million Btu per ton, $8.00 per ton.

[2] Sixteen cents per million Btu, 18.75 million Btu per ton, $3.00 per ton.

[3] Twenty-five gallons of oil per ton of shale.

[4] Thirty-five gallons of oil per ton of shale.

[5] Labor at $5.50 per hour, 2.5 per cent for taxes and insurance on plant investment, 4.5 per cent for maintenance.

[6] Includes onsites, offsites, auxiliaries, five per cent start-ups, 15 per cent interest during construction, and 7.5 % working capital. The plant costs are normalized to 250x10^9 Btu/day of product by assuming these costs to vary with capacity to the 0.9 power,

[7] Capital @ 21.5 %/year

[8] Stream factor .8

[9] Excluding shipment

Table 3

	Input fuel (tons/day)	Thermal Efficiency (per cent)	Total Capital[6] ($ million)	Annual Operating cost ($ millions)	Costs (cents per million B.t.u. of product)[8]			
					Capital[7]	Operating Costs[5]	Coal or Oil Shale Cost	Total Cost[9]
Coal gasification								
Lurgi-bituminous[1]	14,700-17,900	56-60	334-390	21.4-22.2	112.5-131.4	33.5-34.7	47.1-57.1	193.1-223.2
Lurgi-Western[2]	19,600-23,000	56-60	290-390	19.5-23.0	97.6-131.4	30.5-36.0	23.5-28.6	151.6-196
Coal liquefaction	13,200-17,500	60-75	233-373	22-35	78.4-125.7	34.4-54.9	42.7-53.3	155.5-240
Low-B.t.u. gas								
Bituminous[1]	12,500-14,300	70-80	195-200	16-10	65.6-70.0	25.1-28.2	40-45.7	130.7-143.9
Western[2]	16,700-19,000	70-80	195-200	16-10	65.6-70	25.1-28.2	20-22.9	110.7-121.1
Methanol-bituminous[1]	14,900	60-67	279-364	44	94-122.3	68.6	47.8-53.3	210.4-244.2
Oil shale								
Gasification	94,500	74	415	-	Technology sufficiently advanced so .7 stream factor is unrealistic		-	-
Liquefaction[3]	72,900	96	342-360	-			-	-
Liquefaction[4]	52,000	96	276-327	-			-	-

Plant Costs for 250 x 10^9 Btu per day of Various Synthetic Fuels.
Derived from May 1974 Technology Review Article.

[1] Thirty-two cents per million Btu, 25 million Btu per ton, $8.00 per ton.

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[3] Twenty-five gallons of oil per ton of shale.

[4] Thirty-five gallons of oil per ton of shale.

[5] Labor at $5.50 per hour, 2.5 per cent for taxes and insurance on plant investment, 4.5 per cent for maintenance.

[6] Includes onsites, offsites, auxiliaries, five per cent start-ups, 15 per cent interest during construction, and 7.5% working capital. The plant costs are normalized to 250x10^9 Btu/day of product by assuming these costs to vary with capacity to the 0.9 power.

[7] Capital @ 21.5%

[8] Stream factor .7

[9] Excluding shipment

Table 4

	Input fuel (tons/day)	Thermal Efficiency (per cent)	Total Capital[6] ($ million)	Annual Operating cost ($ millions)	Costs (cents per million B.t.u. of product)[8]			
					Capital[7]	Operating Costs[5]	Coal or Oil Shale Cost	Total Cost[9]
Coal gasification								
Lurgi-bituminous[1]	14,700-17,900	56-60	334-390	21.4-22.2	60.7-70.9	25.9-26.9	47.1-57.1	134-155
Lurgi-Western[2]	19,600-23,800	56-60	290-390	19.5-23.0	52.7-70.9	23.6-27.9	23.5-28.6	100-127
Coal liquefaction	13,200-17,500	60-75	233-373	22-35	42.4-67.8	26.7-42.4	42.7-53.3	112-163.5
Low-B.t.u. gas								
Bituminous[1]	12,500-14,300	70-80	195-200	16-18	35.5-37.8	19.4-21.8	40-45.7	95-105.3
Western[2]	16,700-19,000	70-80	195-200	16-18	35.5-37.8	19.4-21.8	20-22.9	75-81.5
Methanol-bituminous[1]	14,900	60-67	279-364	44	50.7-66.2	51	47.8-53.3	149.5-170.5
Oil shale								
Gasification	94,500	74	415	-	75.5	25.0	56.1	156.6
Liquefaction[3]	72,900	96	342-360	-	62.2-65.5	27.0	42.8-48.2	132-140.7
Liquefaction[4]	52,000	96	276-327	-	50.2-59.5	23.4	46.8-52.6	120.4-135.5

Plant Costs for 250 x 10^9 Btu per day of Various Synthetic Fuels.
Derived from May 1974 Technology Review Article.

[1] Thirty-two cents per million Btu, 25 million Btu per ton, $8.00 per ton.

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[4] Thirty-five gallons of oil per ton of shale.

[5] Labor at $5.50 per hour, 2.5 per cent for taxes and insurance on plant investment, 4.5 per cent for maintenance.

[6] Includes onsites, offsites, auxiliaries, fiver per cent start-ups, 15% interest during construction, and 7.5 % working capital. The plant costs are normalized to 250 x 10^9 Btu/day of product by assuming these costs to vary with capacity to the 0.9 power.

[7] Capital @ 15%/year

[8] Stream factor = .904 = 330/365 days/year

James W. Meyer
June 1, 1974

15-1

Working Paper No. 15

MIT Energy Laboratory

"SAVED" FUEL AS AN ENERGY RESOURCE

Energy Demand Measures

There is little doubt that free market forces will correct the demand side of the energy supply-demand equation. The market, never entirely free, coupled with inertia in the many facets of energy demand, often fails to provide the proper correction or fails to affect a timely correction. Policy can and should be applied to correct the market's failure to control demand. To select the right policy we must establish the bases for informed choice and supplement this by an educational program that will make the chosen policy work.

Conservation:

- Increase Energy Productivity
- Eliminate Energy Waste
- Frugal Energy Use

The three most important issues in conservation policy are those which lead to more efficient use of energy, i.e. policy to increase the productivity of energy. In the second approach, policy leads to using less energy; a method already employed, e.g. turning down thermostats to save heating fuels. A third method which, like the first, has a major technological component, is to affect policy encouraging the use of an alternative, less scarce or renewable energy fuel resources. The time scale for using less energy is short, while that for increasing the productivity of energy or for providing alternative sources is comparable to time scales involved in increasing energy supply. The generic term "energy" is used here because measures which result in reduced energy demand in any sector can and will reduce the demand for petroleum products.

The target of a conservation program is waste. We waste more energy than most other nations use. This waste is fully half of the energy we burn. Voluntary measures taken to reduce energy use last winter have produced dramatic results in many areas. The public was asked to take action on measures which were known to reduce energy use. Little quantitative information was available on how much saving these measures would produce or on what the consequences, particularly indirect consequences, would be. Our knowledge is poor on how far to pursue some of these measures. In the recent past, recommended light levels have increased substantially. Reduced lighting levels most certainly will save electrical energy and in the summer, power required for air conditioning. Minimum lighting standards need further investigation, particularly ratios of illumination in contiguous areas.

In the winter of 1973-1974 in New England we saw as high as 20% savings in fuel use, corrected for weather, by operational methods. The high cost of fuel will certainly encourage their continued use. There is a need, however, to get a more quantitative measure of the savings to be expected. Because of the variety of climates in our country and wide differences in our building stock, this quantification should be done on a regional, perhaps on a local basis. Especially when the method requires sacrifice, actual or perceived, on the part of the consumer, it is important to give him a measure of what he is getting for his apparent discomfort. The consumer has already seen the cost of fuel and/or electric power go up as a result of his using less. His bill hasn't decreased.

Positive public response thus far has probably been more to avoid running out of fuel or electric power than it has been to be more economical in face of rising energy costs. If increased prices produce as expected increased supply, it is not at all clear that the economic incentive alone will persuade people to continue to curtail use. There may indeed be more of an incentive to "pass through" increased costs in the form of increased wage demands by workers, and increased prices by marketers. Timely achievement of independence from foreign petroleum import will require continued effort in conservation. It is essential that we develop the bases for informed choice and follow that with a comprehensive public information and educational program.

One might expect burgeoning fuel prices to elicit proper attention to increasing productivity of energy, just as increased worker productivity is a sound, non-inflationary reason for wage increases. We have examples where productivity will have too great a time lag. In situations where increased costs, including increased energy costs, can be fed through to the consumer, and where the product is in short supply, the dominant forces are to increase supply at increased cost. The energy intensive cement industry is a case in point. Past year of surplus production led to the shutdown of non-competitive, inefficient plants. Now we have a forecast cement shortage produced by the petroleum shortage. If costs can be passed through, it becomes "economical" to meet the shortage by reopening the inefficient plants which in turn exacerbate the energy shortage.

The cement manufacturing process has the inherent potential for using high sulfur fuels with no hazard to either product or to the environment. In fact, the sulfur in the fuel reacts with the cement to improve the product! Naturally, at the time of their construction, cement plants locate and operate in a manner compatible with raw material supply, energy supply, and market conditions. Unfortunately for current conditions, the above criteria led to prodigous use of then cheap and then available natural gas.

The cement industry is used as only one illustrative example of the need to reevaluate fuel usage in our various industrial and production processes to establish where fuel shifts can be made economically and productively.

A deterrant to increasing energy productivity and to promoting less energy use in space conditioning is the historical preference for building and remodeling on the basis of first cost rather than on the basis of life cycle cost. Even now, less than 10% of all building projects have only a minimum life cycle cost analysis made. As a result, we have a building stock in this country woefully underinsulated and caulked, and drastically over-fenestrated. There has been little incentive, with cheap and abundant fuel, to design home furnaces and burners for efficiency and reliability instead of low first cost and reliability. Speculative builders do not pay life cycle costs. As a result, we use too much fuel to heat our homes and small businesses even to standards below those of years past.

To attempt to correct this condition only by increasing standards for new construction would be too little, too late. Methods must be devised to encourage and to implement retrofit improvements to the existing building stock. In so doing, we must be careful not to make demands on the same manpower and materials resources required to increase energy supply. Fortunately, it is not the home construction industry that will build the energy facilities, but there may well be competition for certain critical materials or the energy to produce them. Insulation, aluminum, plastics, etc. may present conflicting demands on available resources.

The environmental impact of conservation is positive and significant. Not only does using less energy help, but also increasing energy productivity permits healthy expansion with no increase in pollution. The provision of alternative fuels to petroleum and facilitating fuel switching by all users creates desirable diversity that has great potential for increased national economic activity at reduced environmental cost.

It is well known that remelting scrap aluminum takes less energy than to refine it from the ore. At present, incentives for recycling are not very persuasive. Products are not now manufactured with eventual recycling in mind. Many recycling projects are economically viable only because of substantial injections of volunteer labor. Design and production for efficient recycling will conserve fuel, raw materials, and the environment. The distortion of price has caused a market failure. The market does not now handle environmental costs.

Technology is providing increasing numbers of ways to derive energy or petroleum substitutes from waste. It has been suggested that 2.2 barrels of synthetic crude, ten thousand cubic feet of gas, 430 pounds of charcoal and 80 pounds of tar can be produced from each ton of organic garbage for a capital investment of about $16,000/ton of processing capacity and at a collection and conversion cost of about $20/ton. If all of the more than 7 million tons of organic waste produced in the United States each day could be converted, the output of more than 15 million barrels per day of crude would represent over 80% of our daily crude requirements. Only a fraction of this waste, however, would be accessible to conversion, but only two million barrels of synthetic crude per day from this source would reduce substantially our demand for foreign crude. America produces about a million tons of municipal solid waste a day. Processed solid waste has about 1/3 the heating value of coal and substantially less sulfur.

We have the technology for producing methane from manure, methanol from methane and natural gas, and high nitrogen fertilizer from municipal sewage. We have heard forecast a shortage of nitrogen fertilizer as a result of the natural gas shortage. Until now it has been most economical to make nitrogen fertilizer from natural gas. But this is not the only way. In fact the same plant that produces methanol from methane feedstock can produce nitrogen fertilizer with only a change in catalyst and feedstock. Denitrification of waste water sometimes involves a process which produces carbon dioxide and nitrogen gas. A better process might be one that produces nitrate fertilizer.

The Impact Potential of Demand Reduction

The direct consumption by civilian transportation is about a quarter of the total U.S. energy budget. Indirect consumption represents a significant fraction of industry's 43% of the total budget. General Motors and its products alone consume 10% of the total. The latter percentage does not include the energy cost of the raw materials and finished products used by GM in its operations. Conservation measures which effect savings in fuel consumption can result in far larger savings in petroleum consumption than the direct gasoline savings alone. They can also have a major impact on the economy as a whole.

In "A Report on Automotive Fuel Economy," the U.S. Environmental Protection Agency, Office of Mobile Source Air Pollution Control dated October, 1973 released the results of a major study of the fuel economy of over 4000 cars. This study not only reinforced the findings of numerous other studies to the effect that increased weight is the principal culprit in lowering fuel economy, but also demonstrated that weight was also a dominant factor in the fuel economy of emission controlled cars to the 1973 standards. Cars in the weight range from 2000 to 3500 pounds actually showed increased fuel economy in the controlled 1973 cars over that for uncontrolled (1957-1967) vehicles by 1% to 3%. 1973 cars in the 4000 to 5500 pound class showed 14% to 18% poorer fuel economy than their uncontrolled predecessors.

The growing scarcity of gasoline and its increased cost has already begun a significant shift to smaller cars. This, plus the lowered speed limit, and voluntary reductions through other economics, have resulted in a 20% saving over that predicted for U.S. gasoline consumption. Industrial production dropped 0.5% in December, 1973 because of auto production cutbacks and reduced use of gas and electricity. If the shift to smaller cars is sustained to where 50% of the passenger car population gets 22 mpg on the average, there will be a far greater savings of petroleum products than the 10% of the fuel that is saved.

The smaller car uses smaller quantities of materials. Minerals used by automakers such as iron, steel, aluminum, copper, nickel and zinc are all energy intensive. The use of plastics which grew from an average of 25 pounds per car in 1960 to 125 pounds in 1973 models will diminish. Tires on smaller cars use less rubber and last longer. Smaller cars produce less wear and tear on streets, roads and highways. Feedstocks and process energy for plastics and rubber production will show a reduction per unit built. A recent Bureau of Mines study estimated that if the price of gasoline went from 38¢/gallon to 80¢/gallon, the percent change in consumption of minerals by the automotive industry in 1980 over 1971 levels would range from a 10% increase for 38¢/gallon of gasoline to a 20% reduction for the 80¢/gallon of gasoline.

In light of the strong interactions suggested above, it is wrong to project requirements for oil and gas of 21 million barrels per day by 1978. We need a much better handle on secondary and tertiary effects on energy consumption caused by interactions in these highly connected systems.

Early results suggest that greater than anticipated results were achieved by voluntary conservation measures. It is likely that the greater-than-estimated savings were a result of estimating on the basis of first order effects of measures only. It is only through better estimating techniques and better measures of the results of conservation measures that we will be able to clear up the confusion over the energy shortage and what can be done about the shortage with conservation.

If little attention is paid to ameliorating demand through increased productivity, less use of a scarce fuel, or by switching to a more plentiful and/or renewable resource, experience has shown a tendency to over correct. World sulfur shortages become sulfur gluts...shortages of engineers and scientists were turned into surpluses within a decade.

When trying to survive a shortage, it is difficult to conceive of surplus, particularly in the case of petroleum because it is such an ubiquitous part of our lives. Nevertheless, similarly inconceivable events have happened.

Because of the interrelated nature of our use of petroleum products, conservation in use effects demand in more a multiplicative way than additive. Therefore, if we wait the length of time required for normal forces to work on demand, the chances are we will precipitate a glut not long afterward.

In summary, the thrust of conservation measures to affect reduced demand for petroleum should be:

- Increased energy productivity
- Reduce excessive use

We cannot do this wisely and productively unless we understand both the effectiveness and the effects of our efforts and unless we establish the kind of public educational program that will engender public acceptance and public cooperation with what has to be done.

If we attempt to solve the problem by increasing supply alone, our goal of independence:

- will take too long to achieve
- will likely create a disruptive product glut

Some Specifics on Conservation Measures

Measures for curtailing energy demand, particularly demand for petroleum products, were selected on the basis of ready applicability on a very short time horizon. For this reason, the measures are, by nature, operational or energy management approaches. Such measures do not ordinarily have major secondary and higher order impacts on other sectors. Indeed, a segment of the population has already taken some of these measures to some degree and we have initial indications of their effectiveness. This early data, however, represents the aggregate results of a mix of measures not easily sorted out. Because of their immediate applicability, these measures can reduce demand substantially before we can produce an equally dramatic increase in supply. Incentives in addition to normal market incentives are particularly important if we are to succeed in the short term in effecting a reduction in demand essential to accomplishing "Project

Independence."

The measures discussed here are:

I Living and Working Space Conditions
  - Reduce space heating temperature norms by 3° - 6°F.
  - Increase space cooling temperature norms by 3° - 6°F.
  - Energy management and control in space ventilation (both in design ventilation and air infiltration).
  - Reduce general lighting by one-third.
  - Improve performance of domestic and small commercial heating equipment.

II Transportation
  - Interurban speed limit: 55 mph
  - Interurban passenger car average occupancy increase from 1.4 to 2.4 passengers a car.
  - Collect for burning as a substitute for residual oil used crankcase and waste industrial oil.

III Industry
  - A 15% overall reduction in energy consumption.

These measures accomplished are not so much a lowering of the American standard of living as a reduction in the American proclivity for waste. Per capita energy use in the United States at 310 million Btu is double or triple that of European countries having comparable standards of living: West Germany, 135 million; Denmark, 140 million; Sweden, 160 million; and Switzerland, 90 million Btu per year.

Specific Energy Productivity

I. Winter Reduction of Living and Working Space Temperatures.

Estimates of reduction in fuel consumption resulting from lowering of thermostat settings are based on the degree-day system. Variations in heating fuel demand are assumed to follow the degree-day experience. It is further assumed that one degree-day per day is saved for each degree the thermstat setting is lowered. The fractional fuel saving is then the degree days saved multiplied by the length of the heating season and divided by the 30 year normal seasonal degree days.

The national average annual total is 5,156 degree days for an average heating season length of 212 days. Using these figures, one computes a fuel saving of four percent

$$\frac{212 \text{ days x 1 degree}}{5.156 \text{ degree days}} \times 100 = 4\%/^{\circ}\text{F (National Average)}$$

per degree the thermostat is lowered.

A 265 day heating season for Boston shows a 30-year normal of 5600 degree days. These figures indicate a 4.7% fuel saving for each degree Boston thermostats are lowered.

In a statistical analysis prepared by a Special Task Force Group of NOAA, Department of Commerce,[1] 42 heating seasons, averaged on a state by state basis but weighted for population densities and fuel type showed Gaussian normal distributions for the data and no significant trends. When weighted in this way the 42-year mean (1931-1973) for all fuels is 4,752 degree days with a standard deviation of 203 degree days. For an average heating season of 212 days, one standard deviation represents less than one degree day per day variation. In other words, lowering thermostats by only one degree could compensate fuel demand for a one standard deviation colder winter.

Further analysis showed that the coldest winter in 100 would cause a 10% increase in demand for all fuels; coldest in 10, a 5.5% increase; and coldest in 5, a 3.6% increase.

Most weather variability can be accounted for by a reduction of only 1^{o} - 2^{o} in space heating temperatures. Further reductions will affect economies in the use of fuel.

It is estimated that about 5×10^{12} cubic feet of gas was consumed in the coterminous United States for space heating in 1971. A net reduction of living and working space temperatures by 6^{o} would have cut gas consumption by about 10^{12} cubic feet (10^{12} cubic feet of gas is equivalent to 2×10^{8} barrels of oil).

The estimated total distillate oils used for heating in 1971 was

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[1] "Variability of Seasonal Total Heating Fuel Demand in the United States," A Report to the Energy Policy Office, Executive Office of the President, dated September 18, 1973.

550 x 10^6 barrels. The 6° reduction would have saved 110 x 10^6 barrels. (Average total distillate consumption in 1971 was 3 x 10^6 barrels of oil.)

Experience in New England to date shows 16% savings in #2 fuel oil consumption (corrected for weather) with one distributor reporting a greater than 20% reduction in demand through voluntary action stimulated by forecasts of substantial shortages. Electric utilities report a 12% drop in demand.

The reduction of temperature in living and working space is a demonstrated effective means of curtailing demand. To effect an overall reduction in energy demand incentives will be needed to encourage similar reductions in space heating temperatures by all regardless of the type of fuel used.

II. Increase Space Cooling

As is the case with heating degree days, we have cooling degree days as a useful indicator of energy consumption for space cooling. Cooling degree days are computed relative to a base temperature 5°F less than the desired indoor temperature. For a desired indoor temperature of 72°F the base temperature is 67°F. Each day's average temperature less the base temperature gives the cooling degree days for that day. An increase in space cooling norms from 72°F to 78°F increases the base temperature to 73°F and saves 6 degree days per day for the cooling season. The total annual cooling degree days is rather sensitive to the base temperature. Weather Bureau data averaged over several years for Atlanta, Philadelphia and Minneapolis show the following:

	Base Temperature °F	Annual Cooling Degree Days Atlanta	Philadelphia	Minneapolis
	70	877	584	362
	73	505	338	198
% reduction		43%	42%	42%

About a third of the energy put into an air conditioning system is consumed in humidity conditioning and other fixed losses that will not vary with thermostat setting, yet the above figures still indicate about a 10% savings for each degree increase in the thermostat setting.

In commercial buildings the additional air conditioning load produced by lighting is substantial. A reduction of general lighting levels by one-third will further reduce the energy requirements for air conditioning. Residential air conditioners consume about 300,000 barrels of oil equivalent a day. Assuming 50% compliance with the above reduction in thermostat settings, 100,000 barrels a day would be saved. Commercial systems at a 650,000 barrels a day consumption rate could save over 200,000 barrels a day.

III. Improved Performance of Domestic and Small Commercial Heating Equipment

It is estimated that substantial improvements can be made in the efficiencies of installed oil burning furnaces through cleaning, adjustment and minor repairs. When fuel oil was cheap and plentiful the main objective of periodic burner maintenance was reliable performance during the heating season. This ordinarily does not lead to a greatest efficiency adjustment.

Spot checks conducted in the past have indicated that at least 50% of those burners tested were operating at efficiencies less than need be.

Potential fuel savings range from 33% for burner efficiency improvement from 50% to 75% to about 7% for improvement from 70% to 75%. It is estimated fuels savings by burner tune up will average 15%.

It is also estimated that because of pyramiding safety factors in design, many furnaces are overfired. This is particularly likely when homes are heated to temperatures some 6° below the previous norms. Decreasing the firing rate will increase burner efficiency by decreasing the off/on cycle ratio. An additional 5% - 10% fuel savings should be realizable by using a nozzle with a lower firing rate. A twice-a-year change of firing rate by replacing oil burner nozzles to provide a firing rate for spring and fall about 60% of that needed in mid-winter should improve system efficiency even further. In some burners, it is possible to control the firing rate by adjusting the oil pump pressure.

A third option for increasing the efficiency of some converted furnaces is to add baffling to keep the hot gasses from the combustion in contact with the furnace walls longer for more efficient heat transfer. It is difficult to estimate the savings to be realized by adjustment, adding, or replacing combustion chambers and baffles. A figure of 2% is used here.

On the basis that 50% of the oil furnaces can be made more efficient, effecting fuel savings of from 20% to 40%, the savings from these measures in 1971 would have been from 55×10^6 to 110×10^6 barrels of distillates.

It is not expected that dramatic improvements can be made in gas furnaces because gas is basically a cleaner burning fuel. By careful adjustment of air/fuel ratios, the addition of baffles in some instances, and a reduction of firing rate, however, 10% to 20% savings should be realizable on 50% of the furnaces. In 1971 these measures would have saved from 0.25×10^{12} to 0.5×10^{12} cubic feet of gas.

IV. Reduce by One-third General Lighting in Living and Working Spaces

It is now generally conceded that our living and working space is overlighted by a factor of two for all but special conditions. Moreover, illumination while only about 2.5% of our total energy use, consumes about one quarter of the electrical energy produced. In those regions where major fractions of the electricity produced is by oil or gas, reduction of lighting levels can affect substantial reductions in their use.

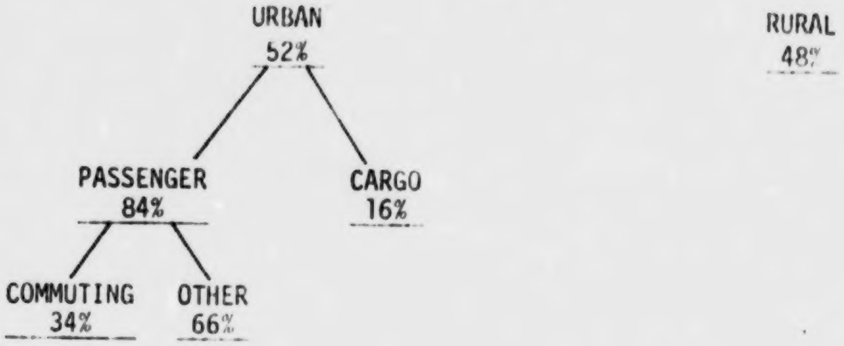
It is true that lighting supplies a substantial fraction of the heat in many buildings, even in the commercial sector where lighting is mostly fluorescent, but it is an inefficient way to provide heat in winter and the same heat presents a major air conditioning load in summer. Substitution of fluorescent lighting for incandescent can provide adequate lighting at greatly improved efficiency.

On the basis of 50% compliance, it is estimated that lowering lighting levels in homes by 30% would save an equivalent of 35,000 barrels of crude oil a day and in commercial buildings, the savings would be about 70,000 barrels a day. Substitution of fluorescent lighting for incandescent today requires a fixture change which discourages the switch to more efficient lighting in homes.

V. Interurban Speed Limit: 55 mph; Increase Occupancy of Interurban Vehicles

The pattern of highway vehicular travel is as follows:

All Highway Vehicle-Miles



Motor gasoline consumption is about 7 million barrels a day. Gasoline mileage for all cars is about 25% less for urban than for rural travel. Rural gasoline consumption is thus about 2.5 million barrels a day. A 10% saving is estimated resulting from a 55 mph speed limit. The savings is thus 250,000 barrels a day.

Intraurban passenger car average occupancy should be increased from 1.4 to 2.4 passengers per car. Of the 4.5 million barrels of gasoline a day used for intraurban travel, about 1.3 million barrels a day are used for commuting. The occupancy increase of one person would cut commuting gasoline consumption by one-third, a savings of 430,000 barrels a day. Increased occupancy for other use could add savings of approximately 350,000 barrels a day.

VI. Burn Used Crankcase and Waste Industrial as an Additive or Substitute for Residual Oil

Waste oil from automobiles and industrial machinery account for nearly half of the oil pollution of the oceans. Porricelli and Storch* estimated that for 1969-1970, 1,440,000 metric tons of crankcase oil and 750,000 metric tons of waste oil from industrial machinery made up 29.4% and 15.3% of the sources of oil polluting, respectively. Tankers accounted for 28.4%, other vessels for 17.3%, refinery/petrochemical plants for 6.1%, off-shore production for 2.1% and tank barges for 1.4% of the approximately 5 million metric tons of oil pollution.

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* D. Porricelli and Richard L. Storch, U.S. Coast Guard, "Tankers and the Ecology," 1971.

Northern States Power Company got encouraging results from a three-day experiment in which waste motor oil was burned with coal to increase the capacity of an electric generating plant, Northwest Petroleum Association reported.

The state of Vermont plants to recycle one million gallons of waste oil a year in a new asphalt refinery of Sprague Oil Company.

The crankcase oil is equivalent to about 10 million barrels and waste machinary oil to about 5 ¼ million barrels. If, as an initial effort, 75% of this were collected and burned in place of residual oil, over 11 million barrels of residual oil would be saved and ocean oil pollution would be reduced by a third.

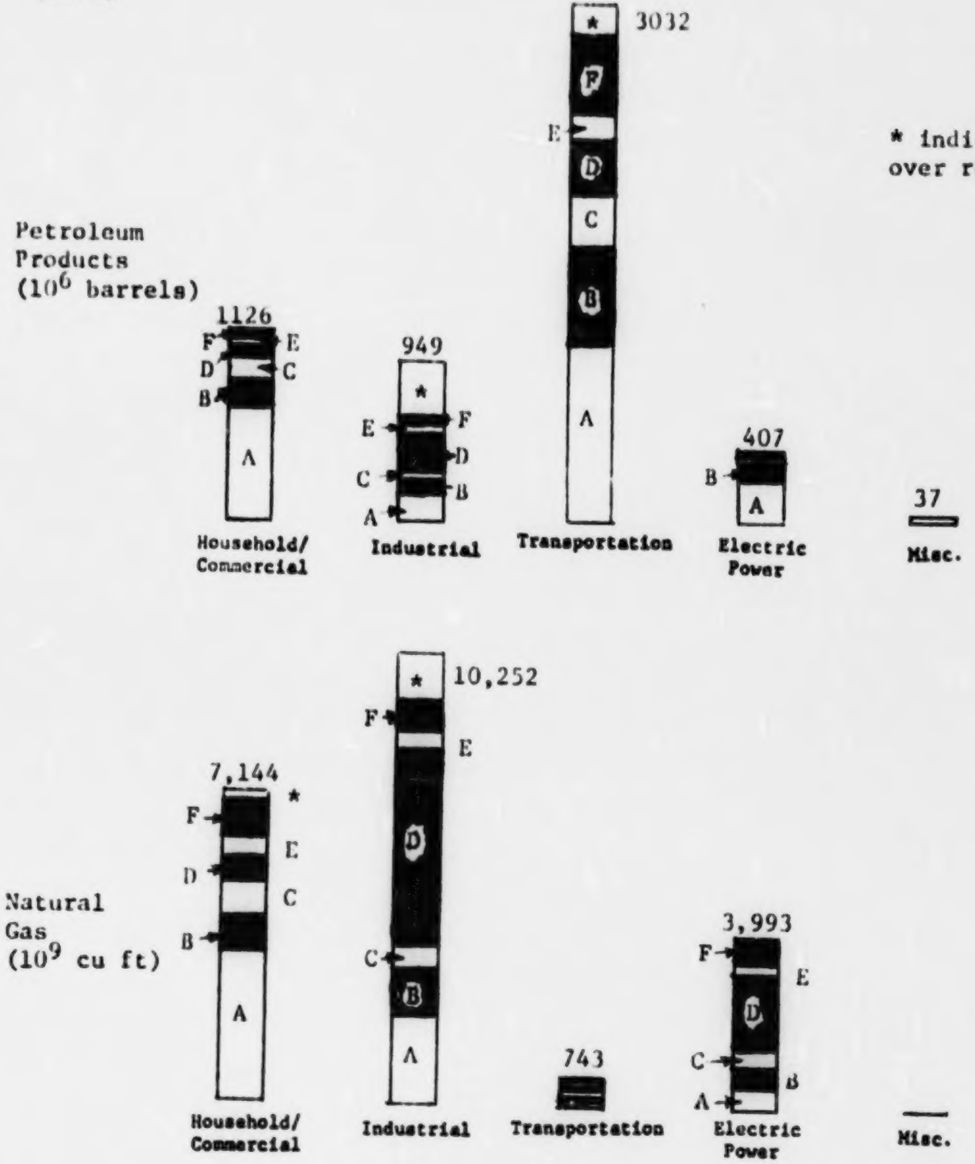
VII. A 15% Overall Reduction in Industrial Energy Consumption

American industry is so diverse that specific conservation recommendations cannot be made; however, several leaders in industry have stated that an average savings of 15% could be made by all industry, principally by exercising good energy control and management practices. Of some 15 industrial programs known to be in progress, initial results would bear this out. Industry consumes in excess of 10 million barrels a day, so an industry wide average reduction of energy use by 15% would save 1.5 million barrels a day.

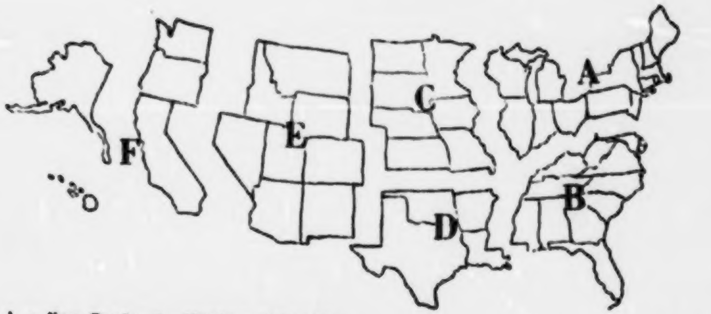
APPENDIX I

In this appendix we have illustrated by bar graph and regional map, the patterns of consumption by fuels, uses, and districts. Also included are bar graphs and tabular presentations of savings to be realized by energy productivity management measures (conservation) in the Household/Commercial, Industrial, and Transportation sectors. Brief analyses of how the savings were estimated are also included.

Consumption by Fuels, Uses, and Districts
(1971)



* indicates amount over regional summary



A = New England, Middle Atlantic and East North Central states

B = South Atlantic and East South Central states

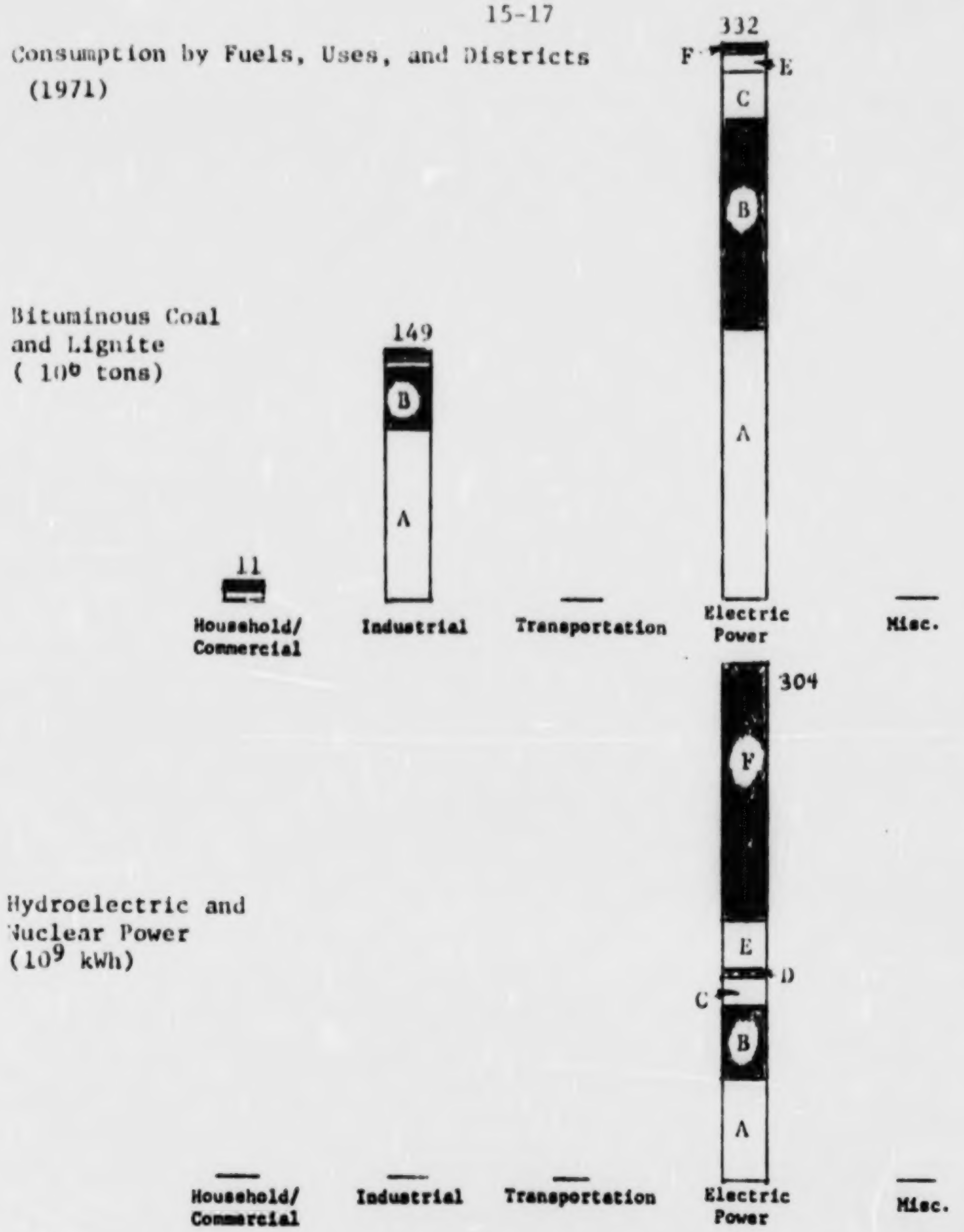
C = West North Central states

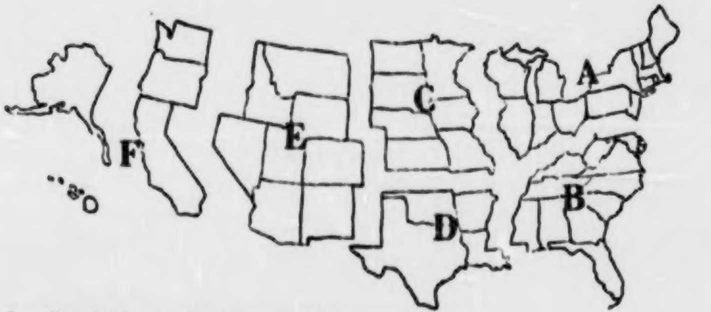
D = West South Central states

E = Mountain states

F = Pacific states

Consumption by Fuels, Uses, and Districts (1971)





A = New England, Middle Atlantic and East North Central states

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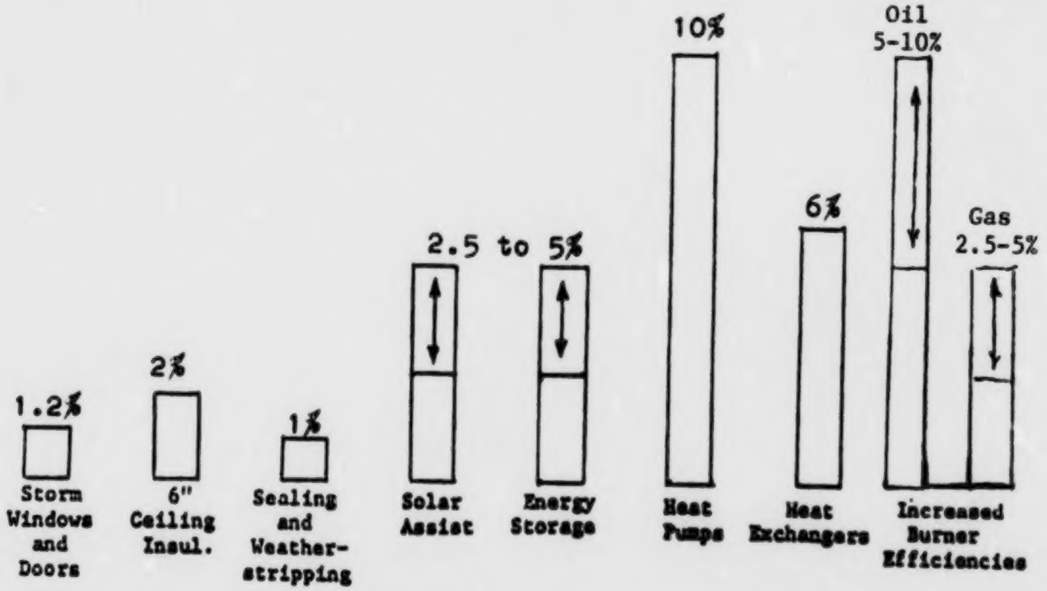
Energy Productivity Management Measures: Household/Commercial



	Storm Windows and Doors	6" Ceiling Insul.	Sealing and Weather-stripping	Solar Assist	Energy Storage	Heat Pumps	Heat Exchangers	Increased Burner Efficiencies
Oil Savings (10^6 barrels)								
Region A	8.	14.	7.	17.5-35.	17.5-35.	70.	42.	35-70
Region B	2.2	4.	2.	5. -10.	5. -10.	20.	12.	10-20
Region C	1.2	2.	1.	2.5- 5.	2.5- 5.	10.	6.	5-10
Region D	.8	1.4	.7	1.8- 3.5	1.8- 3.5	7.	4.2	3.5-7
Region E	.5	.8	.4	1. - 2.	1. - 2.	4.	2.4	2-4
Region F	.75	1.2	.6	1.5- 3.	1.5- 3.	6.	3.6	3-6
Nat. Gas Savings (10^9 cu ft)								
Region A	41	68	34	85-170	85-170	340	204	85-170
Region B	11	18	9	23- 45	23- 45	90	54	23-45
Region C	10	16	8	20- 40	20- 40	80	48	20-40
Region D	7	12	6	15- 30	15- 30	60	36	15-30
Region E	5	8	4	10- 20	10- 20	40	24	10-20
Region F	12	20	10	25- 50	25- 50	100	60	25-50
Electric Savings (10^9 kWh)								
Region A	1.6	0*	1.3	3.3-6.5	3.3-6.5	13	6.5	
Region B								
Region C								
Region D								
Region E								
Region F								

(Regions are as defined on other graphs.)

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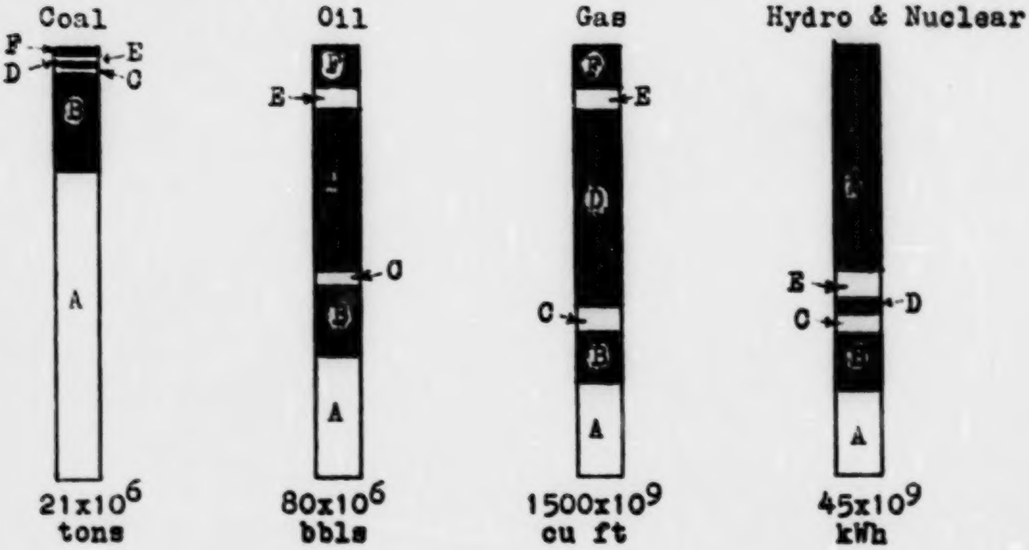
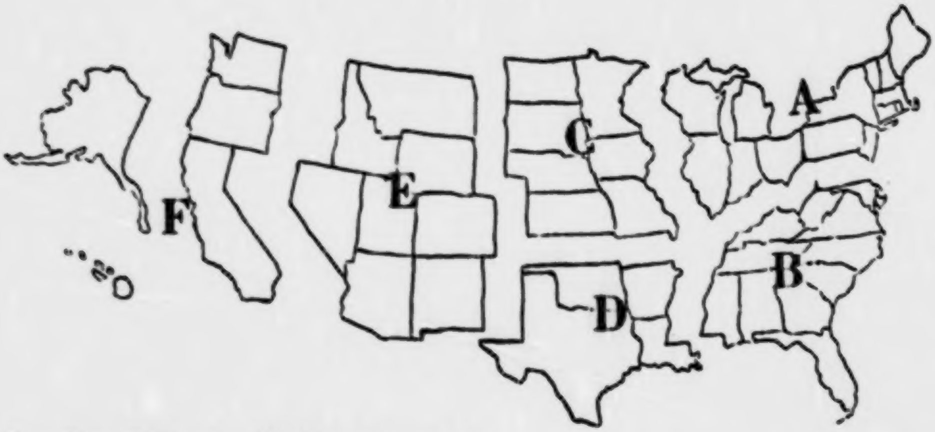
* Electrically heated houses are better insulated.

Energy Productivity Management Measures: Industrial





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ENERGY PRODUCTIVITY MANAGEMENT MEASURES

Industrial

- Improved heat recovery
- Increased furnace efficiency
- Review heating equipment
- Stop heat leaks
- Waste heat utilization
- Waste product as fuel
- Waste product recovery
- Total energy systems

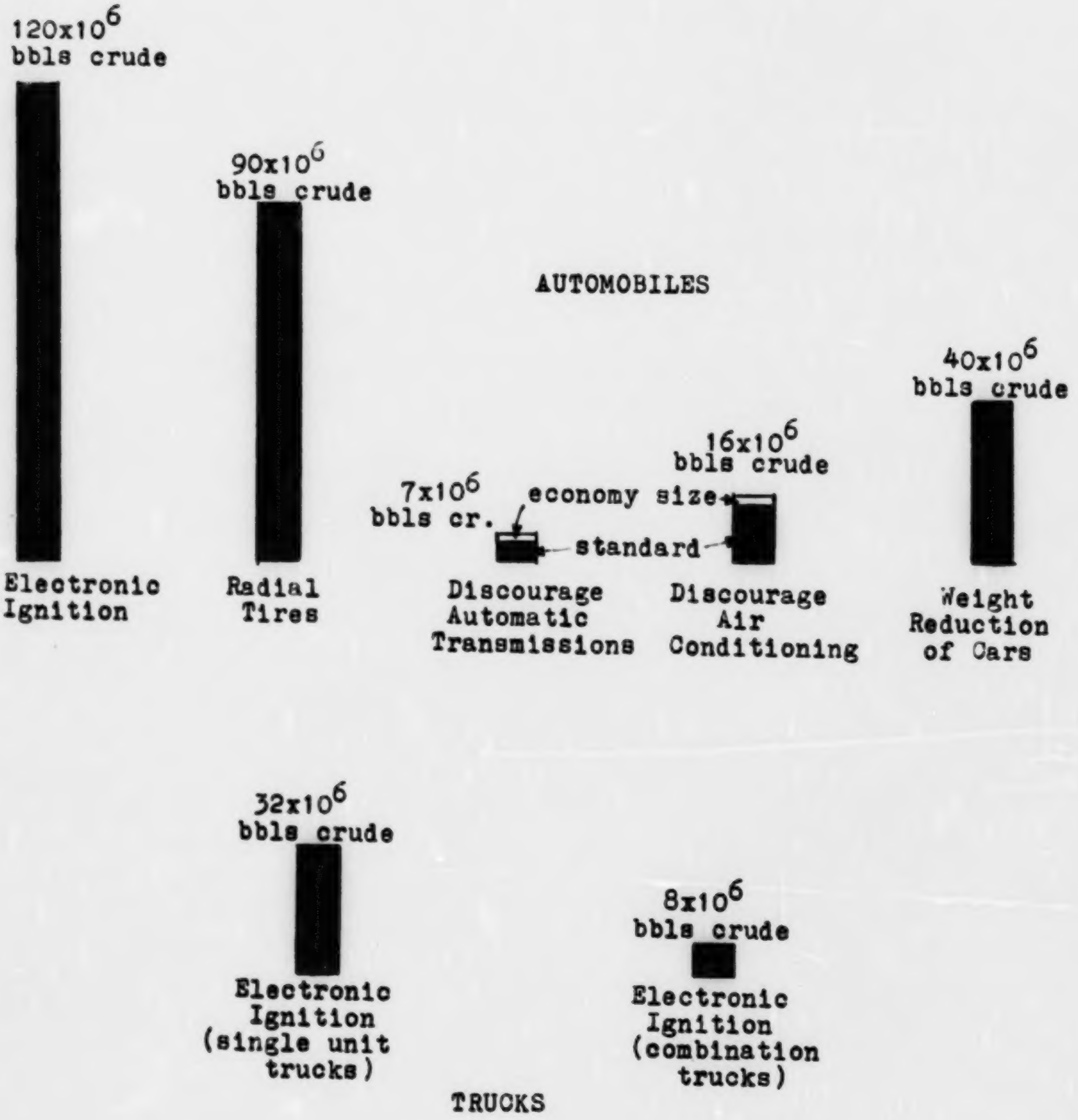
It is estimated that the industrial sector can accomplish 15%* energy savings by a combination of these and other techniques. Companies with energy management programs have done this well and better.

SAVINGS:

Region	Coal 10^6 tons	Oil 10^6 bbls	Gas 10^9 cuft	Hydro and Nuclear Power 10^9 KwHrs
A	15	25	330	9
B	5	12	174	6
C	0.7	3	100	2
D	0.1	30	680	0.6
E	0.6	2.7	77	4
F	0.4	7.4	134	23
	21	80	1500	45

* Note: The 15% savings may not hold for those industries using a rather uniform mix of several different energy sources. In those instances, the 15% savings would be expected to accrue by smaller fractional savings of each source in the mix.

Energy Productivity Management Measures: Transportation



TRANSPORTATION I

Automobiles: 10^8 total numbers

Gasoline consumption 75×10^9 gallons

Oil

Ave. 750 gallons/year per car
(90% Std. 10% compact)

5×10^{-3} gal oil/gal gas
375×10^6 gal oil

Electronic Ignition*

(Retrofit 1/3 car population for 10% improvement in gas mileage @ $150 per retrofit. Total improvement 10% X 1/3 = 3.3%)

Savings: 2.5×10^9 gallons gasoline
or 60×10^6 bbls gasoline (at 50% yield: 120×10^6 bbls crude)

Radial Tires+

(Retrofit 1/4 car population for 10% improvement in gas mileage @$200 per retrofit. Total improvement.

10% X 1/4 = 2.5%

Savings: 1.9×10^9 gallons gasoline
or 45×10^6 bbls gasoline (90×10^6 bbls crude)

* There is considerable question whether the service industry can handle this retrofit volume for installation. The 10% improvement is arrived at by assuming that initially a new mechanical system and the electronic system are equal. It is assumed that the tuned condition for the electronic ignition will last at least twice as long as for the mechanical system. Little data are available on the onset of misfiring, the cause of increased consumption, and how long the average motorist will tolerate slowly degrading performance. If we accept a 20% degredation at the end and linearize the loss of performance, we get a 10% improvement if fuel economy for the transister ignition system. The economics resulting from less frequent tune-ups (1/2 as many) would help pay for the installation. The retrofit envisaged would involve the replacement of points spark plugs, distributor cap, ignition wiring, and coil, plus installation of electronic unit, a procedure not expected to require more than twice the mechanics time of a normal tune up.

+ Radial tires should not be installed on some American cars because of suspension characteristics.

Note: 8% of autos ($\sim 8 \times 10^6$) scrapped each year.

Trucks (Single Unit)

Gasoline	20×10^9 gallons/year	100×10^6 gal oil
Diesel	2.8×10^9 gallons/year	

Electronic Ignition

(Retrofit 1/3 gasoline truck population for 10% improvement in gas mileage @ \$100 per retrofit). Total improvement 10% X 1/3 = 3.3%

Savings: 6.6×10^8 gallons
or 16×10^6 barrels of gasoline (32×10^6 bbls of crude)

Trucks (Combination)

Gasoline	5×10^9 gallons	25×10^6 gals oil
Diesel	5.5×10^9 gallons	

Electronic Ignition

(Retrofit 1/3 gasoline truck population for 10% improvement in gas mileage @ \$100 per retrofit) Total improvement 10% X 1/3 = 3.3%

Savings: 1.7×10^8 gallons
or 4×10^6 barrels (8×10^6 bbls crude)

TRANSPORTATION III

Discourage Automatic Transimissions

Over half the Pintos and Vegas sold in 1973 were equipped with automatic transmissions with a fuel penalty of 6%. Assume 40% of $10 \text{ X } 10^6$ cars sold in 1974 are economy size, and 20% of these American makes. If 1/4 rather than 1/2 of these are equipped with manual transmissions, and similarly for imported cars 10% X 6% = 0.6% would be saved. 10^6 cars X 640 gals/yr-car = $640 \text{ X } 10^6$ gallons. 6% X $640 \text{ X } 10^6$ gallons = $38.4 \text{ X } 10^6$ gallons or

$$\frac{9 \text{ X } 10^5 \text{ barrels}}{1.8 \text{ X } 10^6 \text{ bbls crude}}$$

85% of standard cars sold have automatic transmissions. 60% of $10 \text{ X } 10^6$ cars for 1974 would be $6 \text{ X } 10^6$ standard cars. Assume only half of these are equipped with automatic transmissions, i.e. 35% shift to manual or $2 \text{ X } 10^6$ cars X 900 gallons/car year = $1.8 \text{ X } 10^9$ gallons. 6% X $1.8 \text{ X } 10^9$ gallons = $108 \text{ X } 10^6$ gallons = $2.6 \text{ X } 10^6$ barrels $5.2 \text{ X } 10^6$ bbls crude.

Note: Fully synchronous, 4-speed transmissions would have to be available and heavily promoted or subsidized, or a tax on automatic transmissions might be considered.

TRANSPORTATION IV

Discourage Air Conditioning

Over one quarter of the Pintos and Vegas sold in 1973 were equipped with air conditioning having a 9% - 20% fuel penalty. The 20% penalty occurs in heavy traffic summer driving with a lot of stop and go. In the 1972 model year nearly 70% or over 6 X 10^6 units of American cars had air conditioning. It is estimated that 75% of the standard cars will be so equipped in 1974; 4.5 X 10^6 units, and 25% of economy cars; 1 X 10^6 units.

Assume an average fuel penalty of 15%, cut airconditioning use to 1/2 the cars.

Economy: 0.5 X 10^6 X 640 gallons/year car = 320 X 10^6 gallons/yr.
15% X 320 X 10^6 = 48 X 10^6 gallons or approx. 10^6 barrels.

Standard:
2.25 X 10^6 X 900 gallons/year car = 2 X 10^9 gallons /yr.
15% X 2 X 10^9 = 0.3 X 10^9 gallons or approx 7 X 10^6

Total Savings 8 X 10^6 barrels of gasoline
50% yield 16 X 10^6 barrels of crude.

Incentives would be needed to affect a reduction in air-conditioning use. A tax on airconditioners might be imposed.

TRANSPORTATION V

Encourage Weight Reduction in Automobiles

Data has shown that automobile fuel economy is inversely proportonal to weight. (See EPA Data October 1973). The current technique has been to reduce weight by decreasing size. Weight reduction without reduction in size of standard cars should be encouraged. New reinforced plastics, for example, offer potential for 30% weight reduction. Assume a 15% weight reduction in 6×10^6 standard size cars, saving (15% of 900 gallons/yr.car) 135 gallons/yr.car. The total saving for 6×10^6 cars x 135 gallons/yr.car is 800×10^6 gallons of gasoline or about 20×10^6 barrels of gasoline (at 50% yield equivalent to 40×10^6 barrels of crude).

Fuel Economy

Weight of Car	Fuel Economy Uncontrolled 1957-67	Fuel Economy 1973 car	% Change Controlled vs. Uncontrolled Emissions
2000	23.2	23.8	+2.6
2250	21.7	21.9	+0.9
2500	19.1	19.7	+3.1
2750	17.1	17.5	+2.3
3000	15.4	15.6	+1.3
3500	13.5	13.9	+3.0
4000	12.6	10.8	-14.3
4500	11.7	10.1	-13.7
5000	10.9	9.3	-14.7
5500	10.5	8.6	-18.1

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Appendix Paper No. 16

SAFETY AND ENVIRONMENTAL ISSUES RELATED TO THE LIQUID METAL FAST BREEDER REACTOR AND ITS PRINCIPAL ALTERNATIVES, ESPECIALLY COAL

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Testimony prepared for the Subcommittee to Review the National Breeder Reactor Program, Joint Committee on Atomic Energy, United States Congress.

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(Corrected copy)

ABSTRACT

Besides energy conservation and more efficient energy utilization, the only serious options for generating bulk electric power for the period beyond A.D. 2000 are breeder reactors, controlled fusion, solar power, or coal. This paper provides the Subcommittee a detailed survey of the main environmental and health problems associated with these options, concentrating principally on nuclear power (specific to breeder reactors where possible) and on coal. The other options receive brief mention, and generally present less environmental hazard.

Nuclear power, including the LMFBR, seems much more attractive environmentally than does direct coal combustion, unless strict emission standards are imposed over most of the country, e.g., by stack gas scrubbing, etc. An alternate strategy of synthetic fuels for coal could present much less environmental difficulty, but very possibly at prohibitive expense (for electric power generation).

Under present de facto conditions of little control over emissions from coal burning, the relative hazards of (coal/nuclear) are something like (100/1) against coal. Approximately the same ratio is expected to apply to the relative hazards of coal vis-a-vis fission breeder reactors.

I. The options to be compared.

The nuclear breeder, compared to what? one properly asks. In the long term, by which I mean early in the next century, the choices will be a nuclear fission breeder; controlled fusion; bulk solar power; coal; and/or more vigorous conservation and more efficient energy utilization. Conservation and efficient utilization have been first on my list for several years; much can be done beyond what is being done now.

The main content of this paper will be a comparison of the environmental effects of nuclear power vis-a-vis coal; but the other possibilities deserve some discussion. Some may not actually be really practical, and none is without substantial difficulty.

II. Conservation.

This option is easy and brief in the writing, hard in realization. Up to a limit generally estimated as 30-40% of classic (1972) energy projections, most predictions agree that energy conservation through more efficient use has net beneficial environmental impact. The benefit arises from (a) less pollution via less fuel mined, transported, transformed and consumed; (b) less partly reacted fuel exhausted to the biosphere, in a still highly reactive state. Beyond 30-40% savings, the payoff is unclear, because the total impact of different life-styles is not well enough known. The main obstacles to substantial conservation as a viable option are the attitudes and personal desires of people, and the inadequacy of institutions.

III. Controlled fusion.

Research and development in controlled nuclear fusion proceeds well scientifically, and seems technologically possible; but the outcome is still uncertain. In many technological and engineering ways, controlled fusion will be as far advanced from any fission reactors as fission is from coal-burning. Fusion will cost a lot, and we won't know the total answer for some years yet. Nevertheless, I believe it to be worth the substantial investments made and planned, because of expected advantages in real security, and general environmental quality. However, because no actual fusion reactor has yet been built, what follows is somewhat speculative.

A large fusion reactor, generating (say) 1000 megawatts of electric power, is expected to contain an inventory of not more than 10 kilograms of tritium, one of its most important radioactive materials. Tritium is used as the fuel for the reactor; it is radioactive, with a half-life of 12.3 years, and must be regenerated in the fusion reactor, using neutrons from the fusion reaction. The 10 kg. of tritium would be mainly distributed in the moderating blanket of the reactor, and in the tritium recovery equipment. Its activity is about one billion curies, a great deal. But the relative biological hazard of tritium is very low compared to either fission products (strontium-90, cesium-137, etc.) or the transuranic elements (plutonium, curium, americium, etc.) produced in any fission reactor, whether it is a breeder or not. Best present estimates place the relative toxicity of the radioactive inventory at 1/1000 or 1/10,000 that of an equivalent fission reactor. Those numbers are meant as guidelines only, because they are not yet well determined. In addition, the relative safety of a fusion reactor depends also on it not having a major accident, just as with fission reactors; experience with fission reactors indicates that safety against severe accidents can only be judged with respect to fairly specific designs. No such design yet exists for fusion. But all predictions point to a relatively benign device.

With regard to theft and diversion of nuclear material, the problem does not arise. To be sure, one can make an H-bomb with deuterium (readily available) and tritium; but an A-bomb is needed to trigger it, and there are other even easier ways of making H-bombs (given the trigger). Thus the incentive to steal tritium for clandestine purposes is very low.

No radioactive wastes arise from the fuel cycle itself (except tritium-contaminated items). The high energy (14 million electron volt) neutrons from the fusion reaction will activate the reactor structure itself, the degree depending upon the materials used. Work by Steiner at the Holifield National Laboratory and others shows that the problem of old radioactive reactor hulks should not be worse than that of old fission reactor hulks. That problem in turn is small compared to that of high-level radioactive wastes from the fission process itself.

In summary, then, fusion looks very promising environmentally, but it is too soon to tell with much precision.

IV. Solar power.

It has been glibly said that solar power is environmentally benign. This is not so, except for certain applications, and even then only under certain conditions. Bulk electricity via solar power aims to extract about 20 watts/meter^2 on the average from a land surface covered with equipment. What equipment? Whence arises the environmental impact.

Solar photo-voltaic power plants would operate via exposure of large areas of sensitive devices (many square kilometers). Typical active materials besides silicon (environmentally fairly benign, but expensive) are cadmium sulfide and gallium arsenide. These last two could be eroded away by rain, blowing dust, etc., and the impact of such erosion has not been assessed, to the best of my knowledge. The materials are toxic.

Thermal conversion schemes (e.g., boiling some working fluid to run a turbine-generator) are not so likely to suffer from chemical environmental difficulties, but another remains, common to most solar energy schemes: thermal pollution, surprisingly enough. The problem is that the system absorbs almost all the solar energy incident in the large array of conversion elements, then converts some of it at low efficiency into electricity. Where does the remaining energy go? Waste heat, rejected at the site. Calculations for typical solar power systems show that the resulting waste heat problem is comparable to or worse than that arising from a fossil or nuclear power plant, except that the heat is distributed over the large collecting area.

One can in principle overcome this difficulty by increasing the reflectivity of the surrounding and interstitial areas, thus preserving an unchanged overall heat balance. But so could we paint the desert white (so to speak) any time we wish, to correct for excess heat generation by nuclear or fossil fuels. The end result of this reasoning is that thermal pollution _per se_ is not an in-principle bar to using solar, fossil, or nuclear fuels, a point not generally recognized.(The "green-house" effect from buildup of carbon dioxide in the air, from burning fossil fuels is another matter, to which I turn later.)

V. Nuclear breeder power.

Expected environmental impact of the breeder reactor has been treated in the LMFBR environmental impact statement. Aiming toward a general comparison with coal, I take a somewhat different approach.

The three main hazards to be considered are accidents, diversion of nuclear materials, and storage of nuclear wastes.

(A) Accidents.

The range of accidents is different from the range pertaining to present-day light-water reactors (LWR's); the latter class have been well-studied in USAEC Report WASH-1400, the so-called Rasmussen Report. From reading it, and other independent assessments (by the American Physical Society, by the Union of Concerned Scientists, etc.) I conclude that the final version to be issued this Fall will represent satisfactorily well the situation in LWR's.

Breeders have advantages and disadvantages, compared to LWR's. The breeder reactor itself runs at low pressure, and the chance of a pressure-induced failure in the sodium circulating system seems vanishingly remote; this is the main accident mode discussed for LWR's. On the other hand, the system is filled with chemically reactive molten sodium, and contains more plutonium than do present-day LWR's even after long periods of operation. Also, the reactor core, made of plutonium, is not in its geometrically most reactive configuration, and one can imagine accident sequences that lead to the reactor having a sudden nuclear excursion, in effect, a small nuclear explosion whose consequences are still under examination, and which under some circumstances might be serious.

I am not an expert on guessing what the chance for such an excursion might be, but suggest that no study has been made of the proposed breeder designs comparable to what has been done for LWR's in Report WASH-1400. But I point out, and demonstrate in a later table that the entire LWR reactor accident sequence adds very little to the already small LWR environmental hazard. By admittedly intuitive extension of this reasoning, I would be surprised if the LMFBR presented a significant actuarial risk to the public. It should be small compared to normal hazards encountered by people as they go about their ordinary business. Nevertheless, a study of the consequences and probability of accidents in a LMFBR could and should be attempted, based on the best information and estimation techniques available.

(B) Diversion and sabotage.

This topic will be the subject of another hearing before the Subcommittee, discussed by others more knowledgeable than I. I have some opinions on the matter; for instance, fuel reprocessing and fuel fabrication should be done at the same location, thus minimizing the transport of concentrated plutonium. But I prefer to leave this topic to other sessions and other witnesses.

(C) Waste disposal.

The situation is not appreciably different from that pertaining to LWR's: the wastes are quite similar in character and amount.

The nuclear waste problem is unlike many other environmental problems that arise from materials:

(1) The wastes are in general extremely hazardous to health.

(2) In many cases, the hazard clearly extends well beyond the time horizon of what many people see for effective social control. The question of exporting social cost in time then flavors many assessments and discussions; for example, what effort should be made to reduce social costs (i.e., hazards) to future generations? I believe that solutions are inexpensively available (that is, at very small cost compared to the incremental benefits of generating electric power by nuclear means, over generating it by burning fossil fuels). However, the costs are not zero, and the slight hazards refer to future time - generally the far future. Thus the problem is strictly a moral one: incurring present costs for benefits that can only be realized by others.

(3) Several studies and analyses are now being started, the results of which will clarify the costs and residual hazards of different stratagems of nuclear disposal.

The main hazard consists of wastes from the fuel reprocessing plant: fission products and various transuranic elements; but also some transuranic elements (mainly plutonium) appear with contaminated tools, clothing, etc., mainly from the fuel fabrication activities. Thus we have the following main categories:

(a) Fission products.

The wastes appear almost entirely at the fuel reprocessing plants; and reasonable steps can (and in my opinion, should) be taken to minimize small releases at the reactor site.

The fuel reprocessing wastes represent by far the most active and hazardous category, on time scales up to a few hundred years. The elements almost all have intermediate atomic weights (strontium-90, cesium-137, krypton-85);

all have half-lives less than 30 years, with some exceptions; the exceptions (e.g., iodine-129) could for waste disposal purposes be put into the next category (b) below. Thus after (say) 700 years, the hazard is reduced to one ten-millionth of the original value. Then for all practical purposes the hazard from any given initial lot of fission product waste can be considered terminated at 700 years.

This category of wastes is very important and will be discussed further below.

(b) Actinides from used fuel reprocessing.

These are neptunium, plutonium, americium, curium, etc., formed by neutron absorption, into the uranium of the reactor blanket, and abosrbed into plutonium. The wastes are characterized by extremely high toxicity (especially plutonium), and very long half-life (24,600 years for plutonium-239, and longer for neptunium-237, which dominates everything at very long times). Thus there exists a million-year hazard; since these wastes come with those of category (a) (above), and the hazard of category (a) dominates out to 500 years, our attitude toward these wastes is determined by our sense of responsibility toward generations in the far future.

This category of wastes is important and will be discussed further below.

(c) Low-level contaminated material.

This is principally tools, clothing, etc., used in nuclear fuel reprocessing plants, that has become slightly contaminated, mainly with plutonium.

Recent plans have involved sequestering them in geologic structures such as salt mines, adjacent to the high-level wastes of categories (a) and (b). They have been encapsulated and dumped in

Atlantic ocean deeps by European groups; I am personally unattracted by that activity as a continuing fix, because assessment of the hazards is so incomplete.

No better solution than sequestering presently exists, because of the bulk; chemical treatment options applicable to the concentrated wastes of category (b) are sometimes applicable here, but certainly not universally. Thus the likelihood remains at present that we will be exporting some of these hazards in time; but there are two ameliorating circumstances: (i) because of the extremely low specific concentration, the relative toxicity is not high (e.g., comparable to some uranium ores), (ii) improved technology and operating practices can either decrease the absolute amount, or increase the feasibility of chemically stripping out the active wastes, so that they can be added to those of categories (a) and (b) above. These wastes will not be specifically discussed further; but many of the options discussed below apply, at least in part. The problem requires further study and assessment, and work proceeds, for example at The Batelle-Northwest Laboratories.

(d) Intermediate-level wastes.

There are various kinds, but in general they could for technological and environmental purposes be put into one or another of the above cateogiries: either concentrate and handle them as high-level wastes; or, if the option turns out to be ecologically sound, dilute and disperse them.

I turn now to discuss the high-level wastes in more detail. Substantial parts of this section are based on longer works by

Kubo and Rose[1,2]. The wastes appear in acid solutions when spent nuclear fuel is reprocessed.

Figure 1 shows the relative toxicity of these wastes as presently and typically envisaged. Relative toxicity is defined relative to natural high-grade uranium ore, as described in Ref. 2. The steep decline until 700 years represents the decay of fission products, as described above. The low level persistent remainder at toxicity level 40 represents iodine-129, which will be incorporated for purposes of this discussion with the actinides.

The actinides dominate after 700 years and last about 10 million years; the bump at 10^5 - 10^6 years arises from appearance of decay products not present in the original waste. The actinide level can be changed by chemical extraction, and the figure shows present normal practice -- after removal of 99.5% uranium and plutonium, which is the limit of present nuclear fuel economic incentives.

The two time periods, each with different environmental, social and political implications, are clear from Fig. 1. Were it not for the actinides, the nuclear waste problem could be said to require only 700 year sequestration, which is easy in many geologic formations or engineered structures, and which is even discussable in terms of longevity of social and political institutions. On the other hand, the million year period extends not only beyond the time horizon of social planning and responsibility, but also well

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[1] Arthur S. Kubo, "Technology Assessment of High-Level Nuclear Waste Management", MIT thesis, May 1973.

[2] Arthur S. Kubo and David J. Rose, "Disposal of Nuclear Wastes", Science, vol. 182, 1205-1211 (1973).

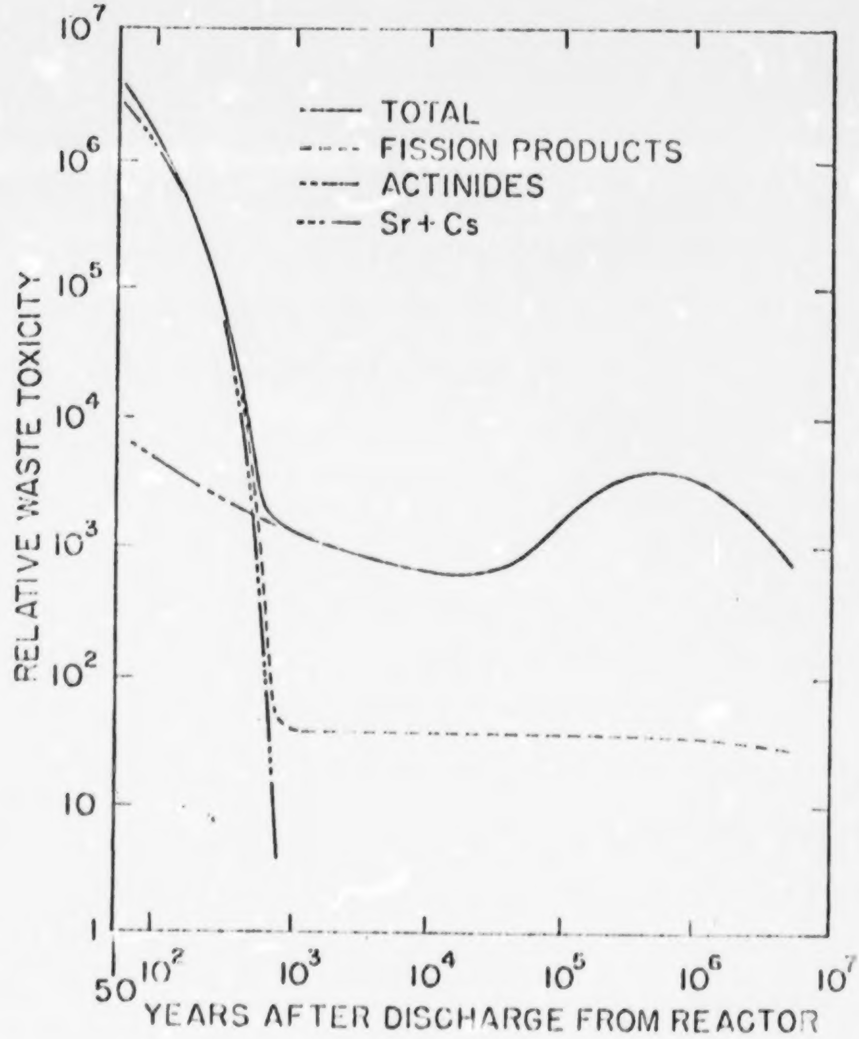

Figure 1. Toxicity of wastes from light water reactors, for an equilibrium fuel cycle, with 99.5 percent removal of uranium and plutonium. Each metric ton of fuel is assumed to deliver a total thermal energy of 33,000 megawatts x days during its operating lifetime. The turn-up at 10^6 years arises from growth of daughter products not present in the original material, which is not in decay equilibrium. The situation with nuclear wastes from a breeder reactor will be very similar.

into geologic time. For example, climatic conditions at Richland, Washington, site of recent leaks from the old weapons production storage tanks, were very different 20,000 years ago, and the future is just as uncertain.

What can be done? Figure 2, taken also from Ref. 2, shows the major possibilities. Waste processing and disposal proceeds downward from the liquid solution, toward final disposal lower in the future. From the late 1950's until 1971, the USAEC, its major contract laboratories working on the problem and the National Academy of Sciences (as program reviewer) bit by bit convinced themselves that the best route was solidification of wastes with characteristics like those of Fig. 1, then shipment and disposal in salt mines, which is route 1 of Fig. 2.

That scheme has merit, if the site is chosen carefully to take into account not only technical but also other factors: possible alternate uses for the land in the long term, for instance.

Other routes on Fig. 2 deserve serious study. A principal one is route 2, where additional actinides are removed, to lower the right hand side of the toxicity curve of Fig. 1 by a factor of about 100. Fortunately, the removed actinides can be re-cycled in a reactor designed to burn them up; thus the long-term hazard vanishes. Rough estimates put the cost of that option at 0.01 - 0.03¢/kwh, about 0.5 - 3% of the cost of generating the power. In shortening the period of concern about the waste repository by a factor of at least 1000, extraction and nuclear burnout of the actinides represents a real long-term hazard reduction. Fortunately, some other routes are worth exploring, especially if the actinides are

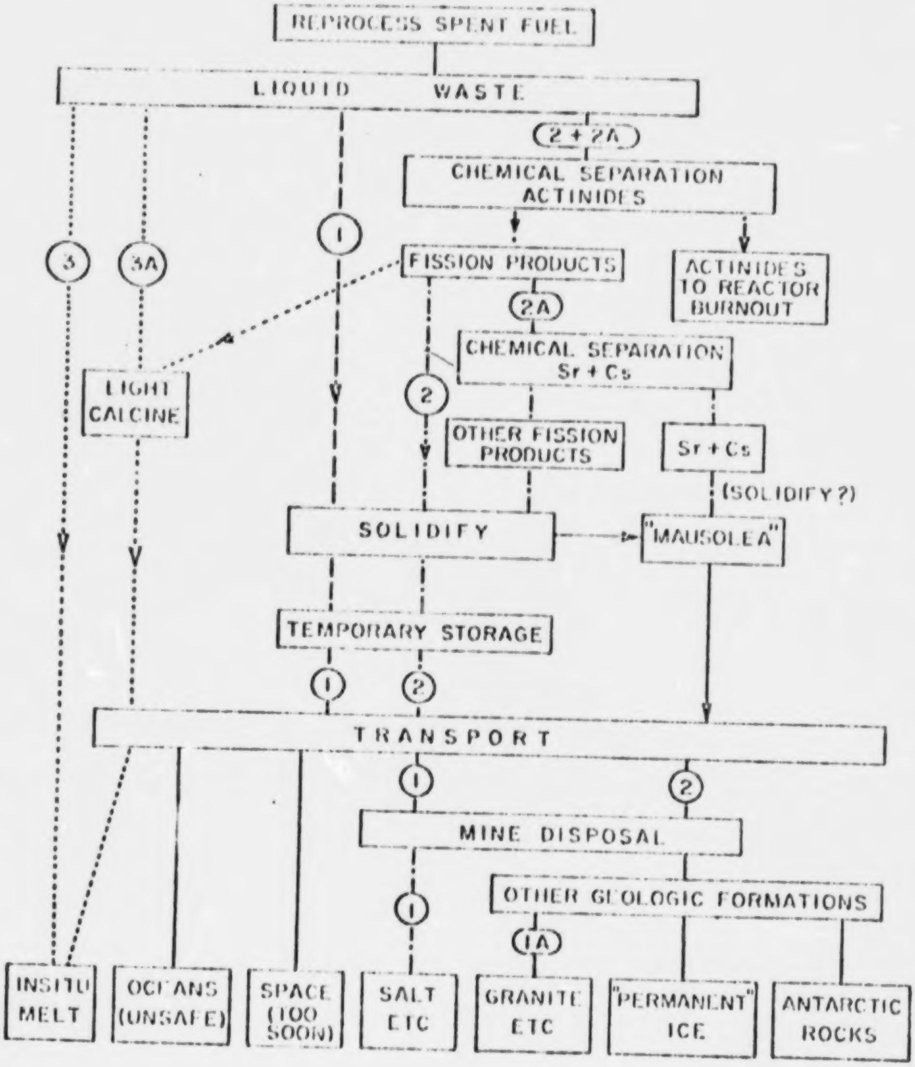
REPROCESS SPENT FUEL
LIQUID WASTE
2 + 2A
CHEMICAL SEPARATION ACTINIDES
3
3A
1
FISSION PRODUCTS
ACTINIDES TO REACTOR BURNOUT
2A
CHEMICAL SEPARATION Sr + Cs
LIGHT CALCINE
2
OTHER FISSION PRODUCTS
Sr + Cs
(SOLIDIFY?)
SOLIDIFY
"MAUSOLEA"
TEMPORARY STORAGE
1
2
TRANSPORT
1
2
MINE DISPOSAL
1
OTHER GEOLOGIC FORMATIONS
1A
INSITU MELT
OCEANS (UNSAFE)
SPACE (TOO SOON)
SALT ETC
GRANITE ETC
"PERMANENT" ICE
ANTARCTIC ROCKS

Figure 2. Taxonomy of nuclear waste disposal options

effectively removed in this way. Storage in granitic rocks, especially those whose drainage paths lead toward the ocean under the continental shelf, is one idea. Even a modification of the melt-in-situ idea, where wastes flow into a specially prepared rock chamber, dry out, heat via their own radioactivity, and fuse into a glassy ball, is worth review. Space disposal is premature, and ice structures seem too hazardous. Disposal in the sea-bed may be a possibility, but the idea requires further careful study.

The cost of these different disposal methods must be correlated with the degree of hazard incurred (or avoided), so that social choices can be made with the best available information.

In general, I think that the nuclear waste problem has been both over-emphasized by the critics, and mis-assessed by the USAEC and its contractees, who failed to recognize many implicit societal issues.

(D) Summary of the nuclear hazards.

A number of overall surveys have been made of the nuclear hazards, especially in regard to light water reactors. Table I from Walsh[3] summarizes the situation there; I expect that the LMFBR will not be more hazardous, because the main hazards have little to do with radiation or reactor accidents, but with normal occupational risks. The data are shown per plant-year of operation, where the plant capacity is taken as 1000 megawatts, corresponding to the large sizes presently in vogue.

Let us focus on the fatalities. The largest contribution comes

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[3] P. Walsh, Environmental Engineers Thesis, Nuclear Engineering Department, Massachusetts Institute of Technology (1974).

Table II.[+] Chemicals and Fuels from a Coal Hydrogenation Plant with a Daily Production Capacity of 30,000 Barrels*

Products	Production, bbl/day	Weight-Percent of Total Product
Tar acids:		
Phenol	428	1.9
o-Cresol	48	0.2
m- and p-Cresol	530	2.4
Xylenols	374	1.6
Total	1,380	6.1
Aromatics:		
Benzene	2,210	8.2
Toluene	3,770	13.9
Xylenes	4,190	15.4
Ethylbenzenes	750	2.8
Naphthalene	790	3.7
Mixed aromatics	1,780	6.8
Total	13,490	50.8
Liquefied petroleum gas	7,300	16.4
Gasoline:		
Motor	5,260	15.6
Aviation	3,660	11.1
Total	8,920	26.8
Grand total	31,090	100.00

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*This plant could also produce 450 tons of $(NH_4)_2SO_4$ and 89 tons of H_2SO_4 per day.

[+] From Reference 6.

from mining and milling the uranium ore - regrettable, conventional mining accidents; one tries to reduce them. Next is reactor operation, and we see the main radiation-related contribution - about one death every ten years somewhere, statistically attributable to radiation from the plant; that number arises principally from off-gas from boiling water reactors, a situation not pertaining to breeder reactors - nor for that matter to new boiling water reactors.

But the main number to focus on is the total - something like one death every two years from one cause or another, attributable to the existence and operation of that plant. The days-off injuries are a little over 500.

Other studies done by other groups, both in the Atomic Energy Commission and outside it, came up with similar numbers, within a factor of about 2. Uncertainties arise for several reasons. For example, does one assign an accident to the year in which the uranium was mined, or the year in which it was put into a reactor? In an industry such as this with growing inventories, differences in accounting yield different results. But the main thing to recall for a little later is the main result - certainly less than one fatality per plant-year, and less than 1000 man-days off.

The table does not seem to contain the item most hotly debated: the probability of large nuclear accidents. But the item is there under reactor operation: a contribution of about 0.01 deaths/year statistically expectable from the sum of every cause listed in the latest revision of WASH-1400. The reactor accident hazard is small in LWR's, and would have to be 100 times larger to equal the contribution from conventional accidents. For example, the largest LWR hazard relates to mining uranium; the LMFBR uses only about 1/100 as much, so that hazard correspondingly decreases.

A more serious concern about nuclear power, in my opinion, is possible collapse of social concern. By this, I mean nothing so simplistically dangerous as a group of sloppy engineers in an otherwise well-functioning society, because such singular ineptitudes are blatant and correctable. What I do mean is nations abdicating their sense of social responsibility, or never having quite had it in the first place. Then little by little, standards decline, quality erodes away, and trouble starts. The predicted low accident rate depends upon the exercise of care, vigilance and responsibility typical of the best parts of society around us. Edward Gibbon, in his history of the decline and fall of the Roman Empire, chronicled fluctuating periods of social concern and neglect during that long epoch. To be sure, modern societies are different, but they have come and gone in the last 50 years, and some have changed from being highly responsible to being relatively incompetent. Unfortunately, the topic is not a good one for analysis; but I choose to believe in a society that trusts itself, rather than one that distrusts itself.

VI. Coal.

Compared to nuclear power, the picture for coal is more bleak. Problems arise principally in two major areas: mining it and consuming it. Associated with mining coal for that 1000 megawatt power plant, we find about one death every two years or so, somewhat above the uranium mining hazard; but that is small compared with coal workers pneumokoniosis, which has disabled tens of thousand of miners, and for which one would have to assign to each coal-burning plant about one hundred miners presently totally incapacitated by coal dust in their lungs. Present U. S. payments for welfare on this account total well over one billion dollars per year. The dust standards are now more strict in mines than hitherto - the limit is now 2 milligrams per cubic meter, which will substantially alleviate the problem in the future.

The problems of consuming coal relate to two different technologies: direct combustion, or conversion to "clean" fuel.

One fossil fuel problem is common to all technologies, has been generally overlooked, and may be the worst environmental danger of all. It is the long-term effect of build-up of carbon dioxide in the atmosphere, which is now calculated fairly reliably to lead to a long-term warming trend via the "greenhouse" effect and quite possibly melting of polar ice caps. Mitchell[4] estimates that the CO_2-driven warming will exceed 0.6°C. before A.D. 2000, possibly moderated by a cooling effect from particulate pollutants (itself not a comfortable prospect). A global temperature rise of 1-2°C. would almost certainly trigger a long-term global change, because sound meteorological theory predicts an amplification of the temperature rise at high latitudes.

(A) Direct combustion.

Burning coal produces particulates, sulfur oxides, and nitrogen oxides. Precipitators can take out as much as 99.8% of the particulates by weight, but fail to remove the very small ones - small in weight and size but serious in health consequences; they can penetrate deep into the lungs, not filtered out by the body's natural mechanisms.

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[4] J. Murray Mitchell, Jr., "A reassessment of atmospheric pollution as a cause of long-term changes of global temperature", in S. F. Singer (Ed.) "The Changing Global Environment", D. Reidel Publ. Co. (1975).

About nitrogen oxides, we know relatively little, but public health authorities are becoming more worried about them as time goes on. The sulfur oxides have been most intensively studied, but even here the data are inadequate. About 60% of coal is burned in electric power plants, so about 60% of the health effects to be discussed can be attributed to electric power via coal.

Air quality standards have been set on the basis of sulfur dioxide concentration - 80 micrograms/cubic meter, but it now seems more of a precursor to a worse offender. The sulfur dioxide oxidizes in the atmosphere at a rate that varies from 1% to 10% per hour, depending on moisture content, presence of fine particulates, presence of metal vapors deposited on the particulates, and so forth, as any introductory book on chemical engineering would confirm. Thus sulfuric acid and acid sulfates travel across the country with the prevailing wind, until they leave, generally over the Atlantic Ocean, or are rained out.

Figure 3 shows the mortality data used by The National Academy of Sciences in their recent study of fossil fuels[5], as worked up by The Environmental Protection Agency. The "Best Judgment" line implies almost total neglect of early data in London and Oslo, and forms the basis of the NAS and EPA mortality estimates. Acid

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[5] National Academy of Sciences "Air Quality and Stationary Source Emission Control", prepared for the Senate Committee on Public Works (March 1975).

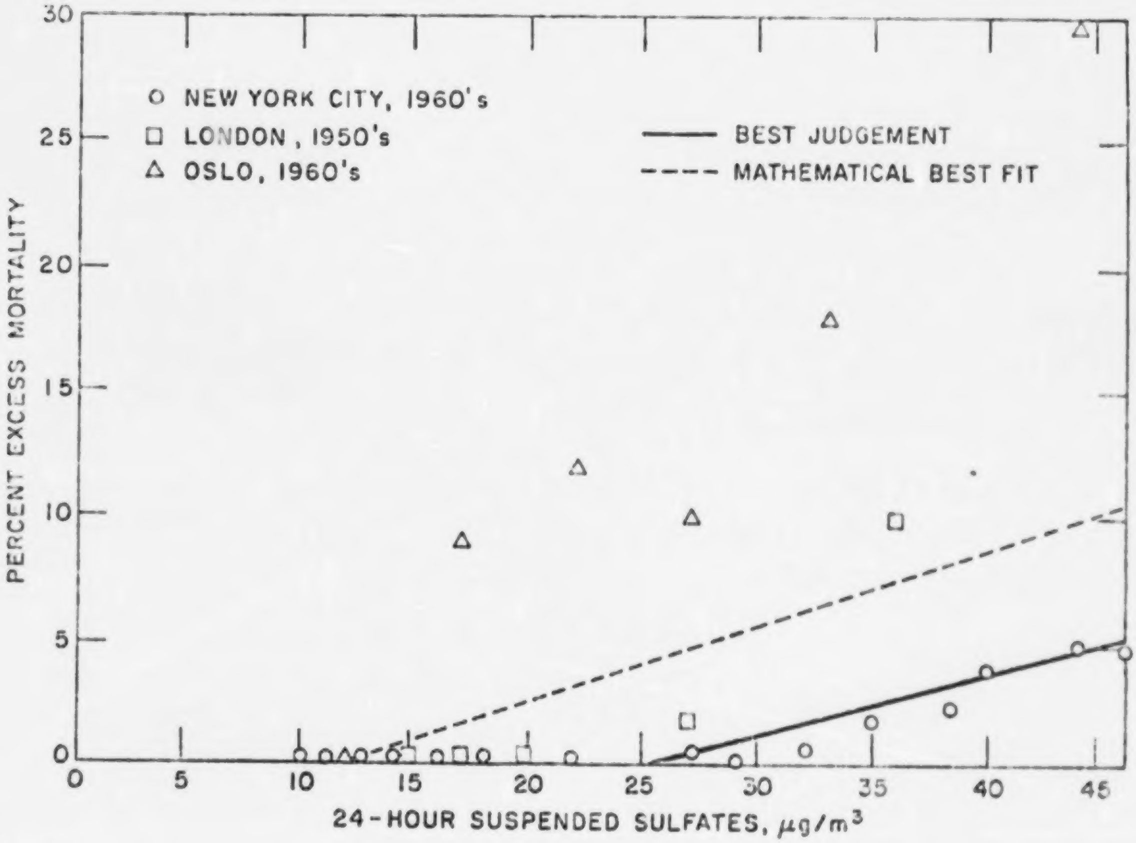

Figure 3. Percent excess mortality expected on account of acid sulfates in the air; from EPA data

sulfate levels in Eastern U. S. urban areas are 16-19 micrograms/meter^3, apparently safe *if* the solid line of Fig. 3 applies strictly, and there is a real threshold at 25 micrograms per cubic meter, as shown. But few would feel satisfied to live so close to danger, especially in view of the large uncertainties in the data. Using Fig. 3, the EPA has estimated that if the 1980 acid sulfate standards are all met, the excess mortality on that account would be very small - in the order of less than one death per power-plant-year. That number is comparable to the nuclear-plant hazard.

However, if the 1975 air standards are not met, or are significantly relaxed, the numbers climb spectacularly: about 4500 deaths in 1980, or some 20 deaths per 1000 megawatt power plant. If the "mathematical best fit" of Fig. 3 be assumed to apply instead, the 1980 deaths jump to about 100 per plant, from air quality deterioration alone. Such statistics entirely overwhelm the nuclear risks of every kind. As one more example of environmental risk, consider expected chronic respiratory disease, as it changes with suspended sulfate level in Fig. 4. Here, the "judgmental" and "mathematical" analyses give very similar results; the predictions are about 6,000,000 cases annually in 1980, if no sulfur restrictions are applied, down to undetectably few cases if all regulations plus conservation are enforced.

(B) "Clean" fuels from Coal.

Three main categories of product can be envisaged: low unit energy gas, high unit energy gas, or a synthetic crude oil. Lurgi gasification and Fischer-Tropsch Liquefaction plants (both dating basically from German World War II technology) are available now, and a few Lurgi plants are being built in the U. S. today. The

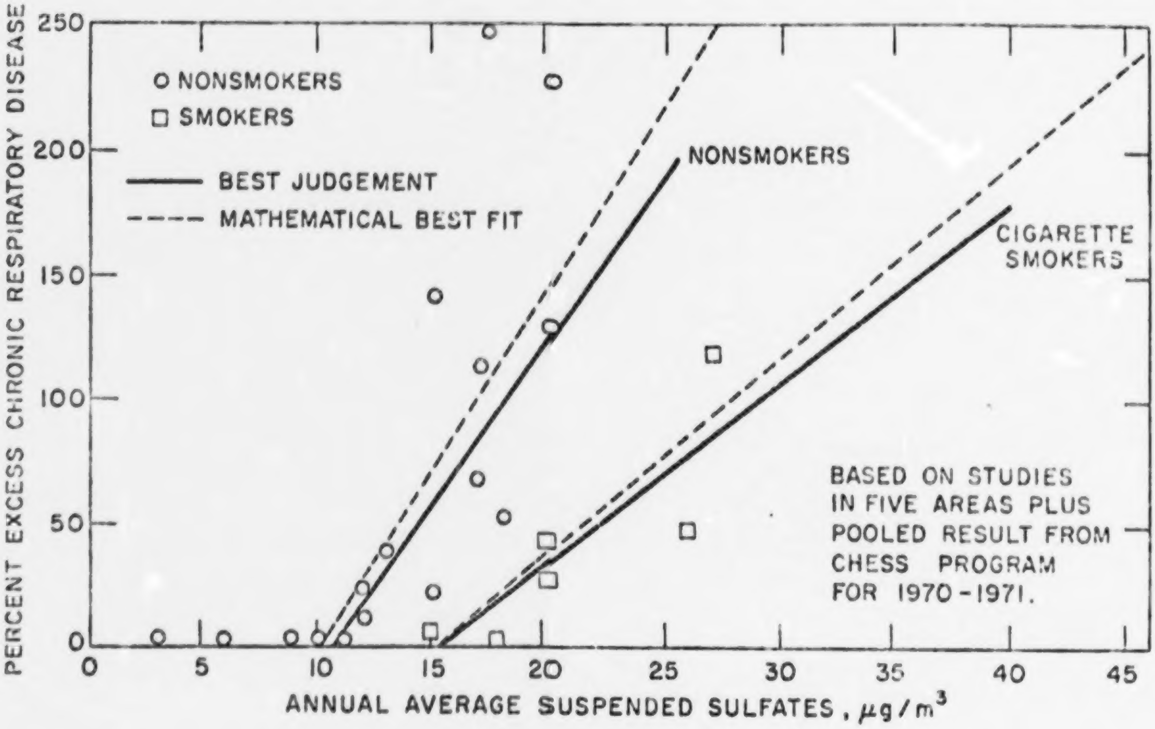

Figure 4. Excess chronic respiratory disease expected from acid sulfates; from EPA data

Wellman-Galusha, Koppers-Totzek and Winkler gasification processes are also commercially available, but not as popular as the Lurgi. Estimates exist that low energy fuel gas and liquid fuel would be attractive propositions to private industry with petroleum at \$15.00/bbl (considering coal at \$20.00/ton), but that high energy pipeline gas (i.e., methane) would probably not. However, all these schemes are relatively expensive compared with burning coal au naturel, followed by stack gas scrubbing. Perhaps unfortunately, the technical situation pertaining to possible health hazards from these processes can be summed up easily: knowledge is fragmentary. However, some useful statements can be made.

1. Pertaining to almost all technologies and products.

a. The plant leakage rates and the characterization of those leakages are not presently well understood, but the leakages can be reduced to arbitrarily small amounts, by arbitrarily large expenditures of money. Thus no matter what the end product, occupational hazards of somewhat indeterminate nature exist. The indeterminacy is compounded by the fact that coal chemistry yields more polycyclic organic compounds; they tend to be more biologically active than long chain hydrocarbons occurring in natural petroleum. Thus about all one can say at present is that synthetic fuel plants will almost certainly be more expensive to bring to the same degree of occupational and environmental safety as now pertains to petroleum refineries.

b. Nevertheless, data can be obtained, and we show below a few examples, as illustrations of state-of-the-art.

c. Many coal-based synthetic fuel processes start with a washing and pre-treatment heating (to prevent caking). This stage produces much dust, SO_2 and perhaps also NO_x. Thus control of all these pollutants will probably be needed at these pre-treatment stages.

d. Many of these processes deal with coal fines, and frothing agents used in their recovery are subject to release.

e. Particulate removal is not automatic in these synthetic fuel processes; for instance, the Project Independence Task Force Report on synthetic fuels makes no mention at all of those in the respirable range, nor does it show knowledge of their importance.

f. Tars and ash from most of these processes will contain sulfur and nitrogen which will remain unless those materials are post-treated; and the tars and oils contain aromatic ring compounds.

g. Water in many proposed locations will be valuable enough for cleaning and re-use; but beware of buildup of heavy metals, etc. Also, the substantial water releases themselves are a health hazard, yet unmeasured.

h. Health effects must be mainly inferred, because few are measured directly.

2. Pertaining mainly to liquefaction plants.

a. The only presently available process is the Fischer-Tropsch, dating from World War II Germany. If that process is adopted extensively soon, very quick work will be needed to correct pollutant releases in present technology. Regarding the products themselves, a small plant typically produces material in the following ratio:

liquid fuel (high in aromatics)	5000 bbl/day
various alcohols	300 "
higher organics, creosote, etc.	100 "

The precise yield depends upon the process, the desired yields, and the coal itself. A Battelle (Columbus) Laboratory Report[6] confirms that "...there is not much current technology to review in this area." Table II from that report gives a modest breakdown into types, from a hypothetical coal hydrogenation facility. Note the preponderance of aromatic compounds and tars.

b. Synthetic liquid fuel is stated to run typically 0.02-0.5% sulfur, determined by regulations and economics.

c. The presence of more polycyclic organics in the final product (than in conventional petroleum) can be overcome at additional refining cost, but we do not presently know the cost.

3. Pertaining mainly to gasification plants.

Here it is necessary to distinguish two main categories:

(1) Low-BTU, intended for use while still hot, on site; and (2) high-BTU, essentially methane as a replacement for natural gas; it is not a likely candidate for electric power provision. A third category, intermediate-BTU gas, is also attractive for some purposes. It is made by a very similar process to low-BTU gas (discussed briefly below), but using oxygen or oxygen-enriched air instead of natural air in the gasification reaction. Thus the intermediate-BTU has has the main difference that it lacks the

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6. Liquefaction and Chemical Refining of Coal: A Battelle Energy Program Report, Battelle Columbus Laboratories, 505 King Ave., Columbus, Ohio 43201; July 1974. See especially page 59.

large amount of nitrogen present in low-BTU gas; as a consequence, nitrogen-related pollutants are expected to be less, but we have not studied the literature in detail to this point.

a. The low-BTU gas option is economically more attractive. The sulfur appears as H_2S, but there is at present no satisfactory hot H_2S removal process. This is important because if the gas must be cooled, much of the attractiveness vanishes. Thus sulfur is a major problem; so also are sludge and waste water.

b. H_2S, once isolated, can be effectively dealt with by the Claus process, yielding 99.5-99.8% elemental sulfur.

c. Because of necessarily local use of low unit energy gas in large installations, the health and environmental problems are substantially site-specific.

The Environmental Protection Agency is publishing a series of evaluations of the various gasification processes.[7]

One can conclude from this discussion that synthetic fuels can be made clean and by clean processes, but at still poorly determined cost. This stands in sharp contrast to the problem of burning coal directly, where the cost can be low, but the environmental and health impact will be severe. Data are woefully inadequate.

VII. Conclusion.

The conclusion about coal is that without strict controls on its use (such as 90% or better removal of sulfur oxides, and probably thorough treatment of fine particulates and sulfur oxides also), coal is environmentally much inferior to nuclear power.

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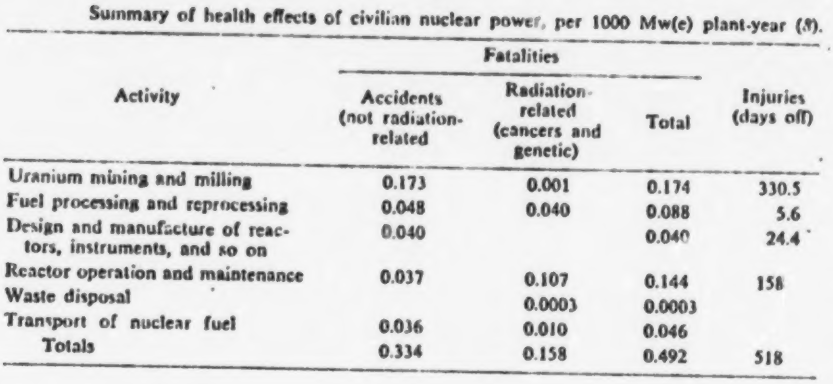
[7] For example, H. Shaw and E. M. Magee, Evaluation of Pollution Control in Fuel Conversion Processes-Gasification: Section 1. Lurgi Processes EPA-650-12-74-009 c. (July 1974).

Each successive study made since the late 1960's has reinforced that general conclusion; yet the general perception persists that nuclear power is unsafe (of course, nothing is safe in any absolute sense); yet we find that burning fossil fuels, especially coal, without strict environmental controls is much worse; even more strange, people tend to shrug off these facts.

Several reasons can be put forward to explain this peculiar response. First, the hazards of reactors and radiation were perceived as "unknown", and hence very possibly large. Second, the public had come to accept the social cost of polluted air, not realizing (i) that much could be done (until recently) and (ii) that its perception of the fossil fuel hazard was faulty. But I think a third reason dominates: over the past 20 or 30 years, the federal government has invested well over $1 billion attempting to measure the public health costs associated with nuclear power, and until recently almost nothing was done to measure similar hazards of fossil fuel power - in retrospect, a scandalous omission. Thus, even with sometimes clumsy words and bad grace, a vast amount of literature appeared about nuclear hazards, providing material for a great public debate. The absence of any appreciable parallel assessment of fossil fuels ensured that the debate would be unbalanced, and only now are semiquantitative social cost figures starting to appear. The profound issue can hardly fail to be resolved in the next few years as more data accumulate, especially on effects of fossil fuels. I conclude from the evidence to date that environmental comparison favors nuclear power; I believe that preference will apply to the breeder reactor also. but with substantially less certainty about the magnitude of the preference.

Table I.



Summary of health effects of civilian nuclear power, per 1000 Mw(e) plant-year (8).

Activity	Fatalities			Injuries (days off)
	Accidents (not radiation-related	Radiation-related (cancers and genetic)	Total	
Uranium mining and milling	0.173	0.001	0.174	330.5
Fuel processing and reprocessing	0.048	0.040	0.088	5.6
Design and manufacture of reactors, instruments, and so on	0.040		0.040	24.4
Reactor operation and maintenance	0.037	0.107	0.144	158
Waste disposal		0.0003	0.0003	
Transport of nuclear fuel	0.036	0.010	0.046	
Totals	0.334	0.158	0.492	518

After P. Walsh, as quoted in D. J. Rose "Nuclear Eclectic Power", Science, Vol. 184, pp. 351-359 (19 April, 1974).

FIRST DRAFT

Appendix Paper No. 17

Solar Energy*

by

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*The 1974 Institute Lecture of the American Institute of Chemical Engineers, presented at Washington, D.C., December 2, 1974.

We tend to think the age of ecology has brought on the interest in the sun as an energy source. Lectures on what the sun holds for mankind have been popular for at least a century. I gave one to the Sigma Xi Society thirty-five years ago*, at which I referred to an unalterable tradition that had grown up, that every lecturer on solar energy must start with a hopefully new measure of its startling magnitude. In reverse, and not new: the sun's mass radiates energy from its surface so slowly that, if the radiation were suddenly turned inward by drawing some sort of magic blanket over the sun and the sun's density and heat capacity were for simplicity taken as that of water, the resultant heating of the sun's mass through 100°C would require half a century. Nevertheless, that minute fraction of the sun's radiation which is intercepted by the earth— which viewed from the sun looks the size of a plum on a tree a quarter-mile away— is of enormous magnitude. One measure of it: the U.S. energy needs in the year 2000 AD, ca. 200×10^{15} Btu or KJ) could be supplied by utilization, with 10% efficiency, of the solar flux on 5% of the U.S. land mass, or on about one-half acre per man, woman, and child.

Another tradition stands: let a scholarly air be lent to the presentation by a few historical references, with slides, preferably ancient. Fig. 1 shows Lavoisier posing with an early solar concentrator; Fig. 2 shows a solar boiler for a power-plant built by Mouchot in Paris in 1878. Mouchot and Pifre in France in the '70's and '80's, Adams in India and Ericsson in the U.S. at about the same time (Ericsson was the designer of the Monitor of Civil War fame, and the builder of Stirling-cycle engines), Willsie in Needles, California, Tellier in France, Shuman in Philadelphia - all around 1909, Shuman in Egypt in 1913 (with Ackermann and the British physicist Boys), Charles Greeley Abbot of the Smithsonian in the 20's and 30's, - all these men spent much time and money, often their own, in the attempt at economically sound use of energy from the sun. Some were scientists turned engineer, some were engineers successful in an area unrelated to solar research. Were they dreamers; or were they on the right track but in the wrong century or decade; or were they on the right problem but ill-equipped to choose the best road to a solution because of the existing state of knowledge? The engineers and scientists and statesmen of the 1970's are having difficulty deciding, and our nation is committing significant funds to improve our capacity to answer. The two pressing questions today are how best to use those funds, and whether they should grow or decline in relation to funds for other energy-related problems pressing for solution.

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* Another measure of time: the price of fuel oil quoted in the lecture was 7¢/gal.!

To make a claim to fairness in the assessment of competing ideas for solar energy conversion by devices not yet invented, one needs clairvoyance. To assess fairly those that have been invented, one must have read all the original literature, have made many independent analyses and numerical computations, and pass on the validity of many cost analyses or, in some cases,— here comes again the need for clairvoyance— join in the game-playing known as projected-cost analysis when the device has never been tested or even built, or join in the Delphic game of guessing whether a poorly established proportionality between unit cost and cumulative production raised to a small negative power, will hold through enough millions of units of production to bring the cost down to a viable magnitude. I haven't read all the literature; I have made some analyses and some computations but not enough to satisfy even myself; and I am no expert on costing. Any assessment of prospects for effective solar energy utilization will in consequence be highly subjective and, if I am frank, will possibly offend more than a few researchers.

Conversion of the sun's energy flux to useful form will follow one of two paths:

1. The radiation may be absorbed at a surface and the resultant thermal energy used for heat or power production.
2. The high thermodynamic potential associated with the sun's energy, as measured by one of its equivalent black-body temperatures (5762K and 5612K are two; there are many others[*]) may be exploited by using the photons in the solar beam to carry out acts consistent with their energy content; and of the solar energy capable of traversing the ozone layer into the lower atmosphere, 80% is in photons of energy content exceeding one electron volt (or in radiation of wavelength less than 1.25μ).

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[*] 5762K is the Stefan-Boltzmann temperature, that of a black body of solar diameter (0.009305 radians at the sun's mean distance from the earth's orbit) which is capable of producing the measured solar constant of 1.353 KW/m^2. 5612K is the half-energy displacement-law temperature, that of a black body half of whose radiation lies on either side of the wavelength that equally divides the energy of the solar spectrum, measured external to the earth's atmosphere. That wavelength is 0.7318μ. Since 5612K is lower than the Stefan-Boltzmann temperature, a "black-body" model calls for either an effective solar diameter 5.4% greater than the true one or for an emissivity of 1.11. For non-thermal applications, 5612K is the better measure, but it should be combined with recognition that very little radiation of wavelength less than 0.32 μ penetrates the ozone layer and that atmospheric absorption further modifies the spectrum. The spectrum itself, modified by the air mass of interest, is of course the only true measure of what a photon-using device sees.

All schemes in the second category are positively classifiable as long range. If man were forced to rely, starting today, on solar energy as a heat and power source, all his plants and devices would fall in category 1. It will be considered first.

Thermal Processes

Before thermal processes are considered, it is desirable to establish some feeling for the magnitude of solar flux as affected by season and latitude. Among the many ways to present such a story Fig. 3 is perhaps as illuminating as any. It underlines the difference between average days and clear days, which latter tend to be uppermost in the layman's mind when he considers the capture and use of the sun's energy. The latitudes where most of the industrialized nations lie are cross-hatched. Space prevents presentation of the enormous effect of microclimate on latitude-average values.

Flat-plate Collectors. In anticipation, the flat-plate collector is in the opinion of a dominant segment of the solar research fraternity and its federal sponsors that device most likely to demonstrate first the significance of solar energy in the nation's energy balance. The sequence of presentation will be: principles of operation, ways to improve, achievements in improving, examples of significance of improvements, applications to space heating and hot water supply, and tentative economics.

The flat-plate collector* is simply a back-insulated radiation-absorbing surface warmed by the sun's rays and, if the desired temperature justifies it, protected against too rapid loss of energy due to back-radiation and convection by being covered with one or more solar-transparent but long-wave-opaque layers of glass or plastic. Fig. 4 shows several designs.

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* To the author's knowledge this term was first used in 1938 and first appeared in print in 1942 (1).

Flat-plate collector performance is given by the relation

$$q_A = S \cdot \overline{\tau\alpha} - U(T - T_a) \qquad (1)$$

where

q_A is the net absorbed flux density, from which the small back-side losses are to be subtracted to yield useful heat flux per unit area.

S is the solar intensity measured in the plane of the collector

$\overline{\tau\alpha}$ is the effective product of transmittance of the coverplates by the absorptance of the absorber plate

T is the mean temperature of the plate

T_a is the ambient temperature

U is the overall coefficient of upward loss from the blackened plate to the ambient air

Division through by S gives the collection efficiency q_A/S.

$$\frac{q_A}{S} = \overline{\tau\alpha} - U(T-T_a) \tag{2}$$

The deceptively simple appearance of Eq. 2 hides the subtly complex problem of optimizing collector design. Possibilities of improvement rest in $\overline{\tau\alpha}$ and U, the dependence of which on various parameters is indicated in the following:

$$\begin{aligned} \overline{\tau\alpha} &= \overline{\tau\alpha}\,[n\ ,\ \rho_G(\theta_1),\ K_G L(\theta_1),\ \alpha(\theta_1)] \\ &= \overline{\tau\alpha}[\theta_1] \text{ for a fixed design,} \\ U &= U[\ \frac{T+T_a}{2}\ ,\ n,\ h_w,\ h_{spacing},\ \varepsilon,\ \varepsilon_G] \\ &= U[\ \frac{T+T_a}{2}] \text{ for a fixed design} \end{aligned}$$

where

n = number of transparent cover plates

ρ_G = solar reflectance at a glass interface

θ_1 = angle of incidence of sun on plate

K_G = solar spectral-mean absorption coefficient of cover plates

L = path length of a solar beam through cover plates

α = absorptivity of blackened surface for solar radiation

τ = transmittance of cover-plate system for solar radiation

h_w = wind-affected external convection coefficient

h_s = convection coefficient across spaces between plates

ε = hemispherical emittance of blackened plate for low-temperature radiation

ε_G = hemispherical emittance of glass for low-temperature radiation

Study of the above indicates the following possibilities of improving performance:

1. Increase n. The higher the collection temperature T, the larger the optimum n
2. Increase τ by use of iron-free glass
3. Increase τ by surface-treatment of the glass
4. Maximize α. A value less than 0.9 is unacceptable.
5. Reduce h_s by increasing the plate-spacing. No gain beyond about 2 cm.
6. Reduce h_s by inserting a thin-walled honeycomb structure between plates.
7. Reduce h_s by use of another gas than air.
8. Reduce ε. Since ε and α are related properties of the absorber plate, a special problem arises; see below
9. Reduce ε_G, also a special problem because of the relation of ε_G to τ.
10. Eliminate internal convective contributions to U by evacuation.

All but one of these principles have been applied; all but two of them add cost to the collector. A few deserve further comment:

3. Lowering glass reflectance for solar energy by surface treatment, thereby increasing τ. When the collection temperature is high, as in application to air conditioning, process heating, or possibly power production, the optimum number of plates may be three or higher. Even with iron-free glass used to minimize internal absorption, the system solar transmittance may be as low as 0.68 unless the glass is surface-treated to reduce the reflectance at a glass-air interface from 0.04 to 0.02. This treatment consists in surface-leaching of Na_2O out of the sodium silicate by use of hydrofluosilic acid. This production of a graded change in refractive index, developed a generation ago, appears to be a lost art, revivable if there is demand. Other approaches, discussed below, may be cheaper. The Löf house in Denver (2) used surface-treated glass.

4. and 8. Absorber selectivity. The importance of this exciting idea, considered in the '40's and prematurely abandoned because the then available materials were not promising*, was firmly established by Tabor's work in the 50's (3). A surface with a monochromatic absorptivity which is very high at wavelengths below 2 microns (spanning the solar spectrum) and very low at longer wavelengths (spanning the spectrum of emitters at temperatures up to 700K) will have a solar absorptivity α which is high and a low-temperature emissivity ϵ which is low. An early but not cheap selective surface, copper oxide on bright aluminum, had the then best selectivity, $\alpha = 0.93$, $\epsilon = 0.11$.** Presently available

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* Oxidized zinc had a low low-temperature emittance, but at too great a sacrifice in solar absorption. Prof. L. Harris at M.I.T. had found that he could deposit by evaporation in nitrogen a thin layer of gold black which exhibited high infrared transmittance and high short-wave absorption, but it had inadequate thermal stability (4).

**α/ϵ is not an adequate measure of selectivity. Keeping α high is much more important for terrestrial applications than keeping ϵ low. A surface with $\alpha/\epsilon = 20$ and $\alpha = 0.8$ is inferior to a gray surface with $\alpha = \epsilon = 0.95$.

materials, such as a thin layer of oxide of nickel or chromium on a layer of bright metal on a substrate chosen for cost and thermal conductivity, are claimed to have $\alpha = 0.92$, $\varepsilon = 0.06$, or $\alpha = 0.93$, $\varepsilon = 0.08$ (5). Fig. 5, showing how thickness of the absorbing layer of oxide affects the low-temperature emissivity and the solar absorptivity (6), illustrates how important it is to control oxide thickness if an optimum combination of α and ε is to be achieved. Structure of the absorbing layer is also very important.

9. Combining low hemispherical emittance of glass with high solar transmittance. This is alternative to — possibly complementary to — the method just discussed. Instead of making the absorber selective, the cover glass may be made selective — highly transmissive to solar radiation but highly reflective to long-wave radiation, with an accompanying reduction in the contribution of radiative loss to the overall heat-loss coefficient U. An electrical-conducting surface layer on the glass, such as tin-doped indium oxide, imparts to glass a low-temperature emittance of about 10% and a solar transmittance of about 85% (7). The concept has some advantages over absorber selectivity.

Other improvements, particularly honeycombing and evacuation of the space between plates, deserve attention. Evacuation is feasible if the "flat plate" becomes a row of parallel tubes inside which absorber strips or tubes are placed. Evacuation of flat-plate systems, with interior-post supports, is not an impossibility (8). A very high efficiency is claimed for a selective-black tube lying on the axis of a larger evacuated glass tube (9). The possible importance of honeycombs is in a state of flux. No more will be said here beyond the comment, quite unnecessary to many readers, that the presence of water in the system undoes the careful work of minimizing U by use of a honeycomb; vaporization of water at the hotter surface and condensation at the cooler one guarantees existence of a built-in thermal leak of large magnitude.

Two plots will show some of the effects discussed, and indicate the range of performance to be expected from flat-plate collectors. In connection with these results it may be said that the agreement between well-designed experiment and rigorous use of the equivalent of Eq. 1 has been so satisfactory that the claim of ability to predict collector performance from the properties of its components combined with established heat transfer relations is now well established (except, perhaps, for the case of the honeycomb, which affects both convection and radiative transfer in a way at present easier to measure than to compute).

Figure 6 compares the equilibrium or no-net-output temperature of collectors of various designs, as affected by the intensity of incident radiation. Included are 1-and 2-glass systems with a standard black absorber, the bottom two curves; a two-glass system treated to produce low solar reflectance; 1- and 2-glass systems using a highly selective absorber; and a 1-glass evacuated system. Clearly, if vacuum is used, one glass suffices.

Fig. 7 shows the efficiency of four of the preceding systems, but all for the rather high solar input of 300 Btu ft^2 hr (0.95 KW/M^2). The figure shows the superiority of selective black and the absence of need for more than one glass if the desired temperature is not too high.

Table 1 compares the relative effects of using a selective black versus a selective glass cover (solar-transmitting infrared-reflecting on side facing black plate) versus evacuating the space between glass cover and absorber plate, for a one-glass collector exposed to solar inputs of 300 and 150 Btu/ft^{2}hr (0.95 and 0.47 Kw/m^2) and operating at 150F and 300F (65 and 149 C). From the table it is clear that choice between selectivity in the glass and selectivity in the absorber plate would depend on cost, since their respective contributions differ by only 3 points; and selectivity in both is not necessary. The improvement due to evacuation is striking.

Table 1. Efficiency of 1-Glass Cover Flat-Plate Collector. (Effect of Absorber Selectivity and/or Glass Selectivity and/or Vacuum)

	Plate Temp=300F		Plate Temp=150F	
	S=300 Btu/ft^{2}hr	S=150 Btu/ft^{2}hr	S=300 Btu/ft^{2}hr	S=150 Btu/ft^{2}hr
Conventional Glass, Conventional Black, Air Space	-	-	0.55	0.24
Conventional Glass, Selective Black, Air Space	0.31	-	0.70	0.56
Selective Glass, Conventional Black, Air Space	0.28	-	0.67	0.53
Selective Glass, Selective Black, Air Space	0.32	-	0.67	0.54
Conventional Glass, Conventional Black, Evacuated	-	-	0.63	0.40
Conventional Glass, Selective Black, Evacuated	0.70	.56	0.81	0.78
Selective Glass, Conventional Black, Evacuated	0.67	.53	0.78	0.75
Selective Glass, Selective Black, Evacuated	0.72	.63	0.78	0.76

Properties Used: Iron-free glass, transmittance for sun = 0.90, or 0.85 when made selective; hemispherical emittance = 0.91 and 0.1 on untreated and treated sides. Absorber surface: solar absorptance (normal incidence) = 0.95 and 0.93 for conventional and selective surfaces; hemispherical emittance = 0.88 and 0.1 for conventional and selective surfaces. Wind and interior-space convection coefficients = 4 and $0.16\Delta^{5/4}$ (Eng. units). $\overline{\tau\alpha}$ = 0.859, 0.843, 0.814, 0.799 for combination in sequence in Table. Ambient temp = 70F (21C).

The picture of performance is relatively simple until the weather is introduced . Figure 8 is an assembly of diverse studies showing the monthly performance to be expected versus collection temperature, all for an ambient temperature of 70F (approximate correction to other Ta's is straightforward), for various collector designs in various localities. Included are winter-average values for vertical collectors in three localities (notice the change from Boston to Blue Hill, only 15 miles away but 600 feet above sealevel, with atmospheric absorption by water vapor significantly reduced); Cambridge values at two different tilts of the collector; performance at Johannesburg and Phoenix; El Paso, showing the effect of surface treatment of the glass to reduce its reflection of sunlight. The two figures chiefly underline the variable character of collector performance and presage some of the problems of using the sun on a guaranteed basis of performance. The same investment produces different returns in different parts of the country; the optimum design can be different for different intended uses of the heat; microclimate, on which data are scarce, may cause large differences in performance for two installations for which the sun's path through the sky is substantially identical.

Space-Heating and Hot-Water Supply

So many solar houses have been built that the safest way not to appear unfair in omitting some is to focus on those with which there has been close personal contact. Fig. 9 shows the first M.I.T. solar house, designed in 1938 and built in 1939-40. It was built as an office and laboratory, not to be lived in, and the objective was to establish the relations describing the performance of flat-plate collectors. The enormous storage tank, capable of delivering summer sun to winter use, was carefully labeled uneconomic, related to the control of experiments and not to the cost of heating.

Fig.10 shows the second or early post-war M.I.T. house, nothing more than a row of thermally separated experimental cubicles to test the concept of combining the collector and the storage unit in a single south-wall element. Predictive computations failed; the leakage of heat to the outside at night in winter, despite the drawing of an aluminized shade between glass panes when the sun disappeared, was greater than calculated, primarily because of air leakage associated with the large pressure difference produced by two shade-separated eight-feet-high slabs of air at greatly different temperature. This, despite the fact that the shade moved vertically in reasonably tight grooves.

Fig. 11 shows the 3rd M.I.T. Solar House, a remodeling of No. 2 into acceptable living quarters for a student family with one child. About two-thirds of the season's heating requirements were supplied by the solar system.

Fig. 12 shows M.I.T. House Four, the first one in the series which, starting at the design stage, was intended for conventional use as a home. Three years' performance data were taken. (640 sq.ft.collector, living area 1450, 60° tilt)

The experience with this series of houses established the following general principles of space heating with solar energy:

1. Quantitative relations available for prediction of performance of collectors of almost any design are entirely trustworthy if the properties of the components are known. But this means knowing the internal absorption coefficient of the glass or plastic; the reflectivity for solar energy of the glass-air or plastic-air interface, expressed as a function of angle of incidence (calculable from the Fresnel equations if the refractive index is known); the transmittance of the cover plates for low-temperature radiation (zero for glass; plastics have some spectral windows); the hemispherical emittance of the cover plates; etc.

2. Year-by-year variation in solar weather at a single locality can produce a 15% variation in performance from year to year.

3. The optimum tilt of collector surface is 15° to 20° more than the latitude.

4. The optimum water flow rate is within 25% of 8 pounds per sq. ft. of collector per hour (40 kg/m^2hr).

5. The provision of more than 24 hours of heat storage is unwarranted.

Fig. 13 illustrates the problem of choice of fractional heating load to be carried by the sun. Across the plot runs a curve labeled"2-pane collector performance" which, because the collector is tilted toward the equator, varies from month to month in a way reasonably favorable to the winter heating season. This curve represents expected performance per unit area of collector. A second curve marked "house heating and domestic water load" is proportional to, not equal to that load. Two values of the proportionality constant - having the dimensions of reciprocal area - are used in plotting. The first one permits the collector to satisfy the load in January, leaving an enormous amount of collectible but non-usable energy for all other months. A second curve, dotted, corresponds to a proportionality constant 1.6 or 1/.645 times the first one. This corresponds to a collector area 64.5% of that required to handle the January load, resulting in the need for some auxiliary heat from November to March but involving the discard of much less collectible heat in other months. Quantitative interpretation of such plots, permitting a balance of fuel saved versus fixed charges on the investment in collector surface, leads to the firm conclusion that in almost no part of the U.S. where heating is a problem can one afford a complete solar heating system. A collector system with an acceptable load factor cannot handle winter peaks. The moment an auxiliary heating system is put in, one stops worrying about more than 24 hours of solar heat storage. Two dull days in a row happen infrequently enough to cause half of a two-day storage system to operate at too low a load factor to justify it.

What is the future of space-heating and water-heating? The load factor for the latter is clearly much better than for house-heating. There are many parts of the country where an annual collection of 12,000 Btu/sq.ft. collector surface per month is feasible*. If there is year-round need, the 144,000 Btu collected-and-used in a year is the approximate equivalent of 1.4 gallons of fuel oil burned at 70% efficiency.

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*And somewhere a significantly higher figure is applicable. The calculated performance in March 21 in Colorado on a clear day corresponds to twice the above figure (^{10}); more significant is the average for the heating season.

If a value of 60¢ is put on that heat and capitalized at 10%, $6 is available per sq.ft. of collector and associated system. If space-heating is considered, a moderately under-designed collector receives only about 5 months of full use, two of half use, and 5 of perhaps one-third use (for hot water). The value of the heat collected, on the preceding basis, has dropped to 38¢/ft^2. For comparison with this oversimplified estimate, an updating of the value of heat collected in one season in M.I.T. Solar House 4, to take account of present fuel prices, yields a figure of 50¢/sq ft.

Though $5/ft^2 won't begin to buy and install the collector, insulated storage tank, pump, piping and controls, such factors as the possibility of improvement in collectors to the point where their energy can be used for summer air-conditioning, the possibility of fuel costs rising faster than steel, glass, and labor, and the existence of significant areas of the country where the monthly average performance is higher than the figure used above, all make the use of the flat-plate collector for space-heating well worth encouraging.

The federal government is now in process of stimulating the growth of a solar-collector and solar-heating industry, through demonstration projects on public buildings. The hope is that as space and water-heating begin to prove economically sound the cost of collectors will come down as a result of volume production. Present costs vary enormously, and there is no correlation between cost and performance. High technical talent is required to design a good system and to decide whether a particular solar climate justifies installation of solar heating; and the gullible public is going to be in need of protection against promoters making unrealistic claims of performance and savings.

Space heating represents somewhere around 18% of our national energy budget. If 10% of the nation's homes were partially solar heated by 1990 - and those would have to be new homes; retrofitting is generally too expensive - and those homes were two-thirds supplied with solar heat, the reduction in our conventional energy consumption would be 1.2 percent. But it would be well worth doing. And if improved collectors can deliver heat at higher temperatures, industrial process heat represents an additional market.

Thermal Power from the Sun

A thermal power plant design which has been brought to a stage where tentative assessment is possible is the east-west cylindrical parabola with north-south diurnal tracking, with a steam-generating tube at its focus. This concept was originally tried in Eqypt by Shuman in 1913. A study by Aerospace (11) indicates the possibility of a collector and transport efficiency of 45%, a loss in thermal short-time storage of 2%, and a turbogenerator efficiency of 30%, giving an overall conversion, sunlight to power, of 13.2%. The total insolation on the aperture of the parabolas is estimated to average 72% of normal incidence because of unfavorable morning and afternoon angles. Three different power-plant designs, baseload, intermediate load, and peaking plant, were analyzed. The cost of the solar baseload plant at the year of commercial operation, in 1990 dollars, was estimated at $2385/KW compared to $572 and $528 for nuclear and coal plants in the same year. Baseload power from the solar plant would cost 38 mills, from the others, 18 to 26 mills. When it is remembered that peaking power is justifiably more expensive than base-load power, and that peaking loads of power grids come in the daylight hours not too far removed from the hours of best solar-plant performance, it is clear that if a few hours' thermal storage for the solar plant is not too expensive, use of the solar plant to supply the peaking load might be attractive. The optimum peaking power solar plant, with 3 hours thermal storage capacity and with reflectors covering 15 $\overline{\mathrm{Km}}^2$ is estimated to produce, in 1991, peaking power for 112 mills/KWH, whereas nuclear, coal, and combined-cycle plants will lie in the range 85 to 115 mills.

Now comes the qualification on these cost comparisons. Collector costs were assumed $25/square meter, or $2.32/ft.^{2}. I have always believed that guided systems, structured to move and withstand wind loadings, and provided with good-quality reflecting surfaces, will cost several times as much as stationary non-focusing plate systems. I can't believe the cost estimate is realistic.

A thermal power plant receiving much attention these days is the tower power plant. Fig. 14(12) illustrates such a plant. Somewhat south of the center of a field of thousands of heliostats is a 1500 foot high tower with a steam boiler on the top and a turbine-generator at its base. Each heliostat is a flat hexagonal reflector 15 feet across, tracking the sun and reflecting the flat-mirror spot together with its penumbra due to solar diameter and mirror imperfections onto the central receiver on the tower. It is simplest, for visualization, to consider those heliostats lying on that ground line through the tower base which is in the plane of the sun and the tower. A little consideration will indicate that heliostats which are too close together will shade their neighbor when the altitude α of the receiver viewed from a heliostat exceeds the solar altitude γ., And when the sun is higher in the sky than the receiver, some of the radiation will be blocked by a neighbor heliostat on its way to the tower. If the heliostats occupy a small enough fraction C_H of the ground they occupy, however, they will not shade or block one another. With C_U representing the local ground utilization factor — the ratio of useful interception to that which the associated ground could intercept if normal to the solar beam -- the above considerations are summarized in the statement

$$C_U = \text{least of } \sin\gamma,\ \sin\alpha,\ \text{or } C_H \cos\frac{\gamma-\alpha}{2}$$

where $(\gamma-\alpha)/2$ is the angle of incidence of the sun on the heliostat surface. Unless the third of these terms is the smallest most of the time, a heliostat will be accounting for less energy transfer than is consistent with its size. Consequently, the heliostats, representing about 80% of the total plant cost, must not have an area more than 0.3 to 0.4 of the ground area with which they are associated; they will vary in spacing in dependence on the part of the field they occupy, and differ from one another in their contribution to $\overline{C}_U$, the field-average value of C_U. The total flux-uncorrected for losses — onto the receiver from a field of heliostats of total ground area A_G will be $\overline{C}_U A_G I_D$, where I_D is the direct or normal-to-receiver intensity of solar flux.

A flux concentration factor C_F at the receiver of about 1000 is proposed. C_F is the ratio of flux density on the receiver to that on level ground. It is related to the geometrical concentration factor C_G, the ratio of total heliostat area A_H to receiver area A_R. The fairly obvious relations are

$C_G \equiv A_H/A_R = \overline{C}_H A_G/A_R$

A_G = total ground area of field of heliostats

$A_R = a(\pi/4)D_i^2$

D_i = heliostat image diameter

$= D_m + (.0093 + 2\sigma)S$

D_m = heliostat mirror diameter

a = a shape factor, about 3

σ = pointing error of heliostats + mirror-flatness error

S = maximum slant range, heliostats to receiver on tower

$$C_P = \frac{\overline{C}_U}{\sin\gamma} \frac{A_G}{A_R}\eta = \frac{\overline{C}_U}{\sin\gamma} \frac{C_G}{C_H}\eta$$

η = reflection and absorption efficiency of mirror and receiver

The term "a" in the expression $A_R = a(\pi/4)D_i^2$ deserves comment, for historical reasons. The area A_R of the receiver should be as small as is consistent with intercepting all heliostat beams, and the limiting images come from those heliostats located on the rim of the field. If the receiver were spherical, "a" would be 4. But it may be shown (see Fig. 15, bottom figure) that A_R is smaller if the sphere is replaced by a segment of a sphere surmounted by an inverted truncated cone tangent to the sphere. In the present example "a" is about 3.3*. The two-dimensional equivalent of this shape was first suggested by the British physicist Boys for use in Shuman's African experiment(13).

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* Exactly, $a = 2(1 + \sin\theta) - \cos\theta$, where θ is the half-angle subtended by the field rim at the receiver.

Collected and concentrated solar energy has a fuel-equivalent value, and a cost comparison of the above-described tower plant has been made on this basis (12), with omission of consideration of the remainder of the tower plant. It is concluded, on the assumption that coal will cost \$23/ton at the half-life of the solar plant, that the two sources of energy will at that point in time be competitive. Since almost the whole cost of concentrating solar energy at a tower receiver is the fixed charge on capital and since the capital cost is composed 80% of heliostats, the cost of heliostats is of interest. Before that is given, a heliostat will be described in more detail. It is set on a concrete foundation to guarantee accuracy in pointing control. To allow tracking of the sun it is provided with a horizontal bearing and a second bearing at right angles to the first. Quarter-inch back-silvered flat glass is mounted on a hexagonal steel channel-beam frame with six spokes to a center plate. Two guidance systems are provided for each heliostat, one open-loop system to point it within 50 milliradians of the sun's center, and a second closed-loop system to seek the solar center within 2 milliradians (the sun's diameter is 9.3 milliradians). The whole system contains about 20 m^2 or 200 ft.^{2} of reflecting surface, and the estimate on cost that makes tower power interesting is \$2.50 to \$3.50 per square foot, or \$500 to \$700 for a complete heliostat with foundation, guidance systems, motors and gears!

Another tower power study (14) is based on the concept of dividing the total plant — in the present study a 100 Mwe plant to be located in central Arizona — into eight sub-fields, each with its own 300-to 400-foot tower supplying steam to the system center where the turbine is located.

The eight sub-fields are terraced to improve the heliostat shading-blocking problem. Each heliostat, 20 by 20 feet, consists of 16 five-by-five foot back-silvered flat glass plates, each distorted by edge-and-center constraint into an approximately spherical segment to reduce the necessary size of the receiver, which is a black-body aperture inside which the heat-transfer tubes are placed. For a 100 Mwe plant capable of delivering rated output for about ten hours per day, 14720 individual heliostats are required, of area equal to 38% of the ground area they occupy, eight 45-acre sub-fields. The thermal collection efficiency — the ratio of absorbed energy at the receiver to direct solar incidence on the heliostats if they were all normal to the solar beam — is estimated to be 60.6%. This allows 0.84 for the mean value of the cosine of the angle of incidence of the sun on the heliostats, 0.85 for mirror reflectivity, 0.96 for optical accuracy and 0.925, 0.96, and 0.995 for reduction by convection losses, reflection losses, and insulation losses at the receiver. The turbine-generator efficiency is taken as 0.35. The mean direct solar flux density for ten hours is taken as 0.86 $KwTh/m^2$ (80 w/ft^2), a figure supported by weather studies.

What appears to the present author to be a realistic economic analysis, in January 1974 dollars, of power costs from a 100 Mwe plant is in process; it produces the following figures: Land is purchased for $700/acre. Common to the solar plant and a fossil-fuel plant is a capital cost of $15.5 M. The additional fossil plant capital cost is $1.9 M (AEC and FPC reports of 1972 and 1973, corrected to 1974 dollars, support the fossil-fuel total of $17.4 M.).

The additional solar plant capital cost is \$16.7 M exclusive of boilers, superheaters, heliostats and their controls. The mentioned items are in process of being estimated; preliminary cost estimates for heliostats and their tracking controls and gear are \$30 M to \$40 M (\$5.10 to \$6.80/ft^2.). Fuel cost for the fossil plant is put at \$1.7 M, which corresponds to 30¢/M Btu and a load factor of 0.73. Estimated operating costs of the two plants, ex-fuel, are comparable, \$254,000 and \$288,000 for the solar and fossil plants, respectively. Here the analysis ends. To obtain a tentative estimate of costs let the solar boiler and superheater costs be taken as \$1.9M and let a fixed charge of 15 percent be used. The fossil plant with a load factor of 0.73 will produce power at 7.2 mills/kwh (fuel 2.66, operation 0.45, fixed charge 4.08) and the solar plant operating ten hours a day will produce power at 27 to 31 mills/kwh (operation 0.70, fixed charge 26.3 to 30.4). One may question the estimated heliostat and boiler costs and the value used for fixed charge, but the analysis serves as a basis for tentative judgement. It indicates that the projected solar plant cannot be considered competitive with fossil fuel plants until the major solar-plant cost—heliostats—is capable of reduction to one-half its already very optimistic minimum of \$5.10/ft.^{2} and, simultaneously, fossil fuel costs increase six-fold.

It is difficult to see how thermal solar power will have any interest until coal and fuel from oil shale cost many times their present cost, and until uranium costs many, many times its present one. Research on thermal power, small-scale low-cost effort that gives ideas a chance to emerge, is justified. Detailed study of the receiver for a tower power plant, the clogging of offices with the accumulated results of computer programs which superimpose a thousand image details from a thousand heliostats onto a receiver to see if tube number 4371 will burn out -- that is like designing the doorknobs for a house to be built in a swamp before the house foundation details have been worked out. Studies of how to design the minimum-cost heliostat deserve to continue.

No mention has been made of thermal power plants based on the flat-plate collector. The relatively low temperature at which solar energy can be collected efficiently and particularly the cost of movement, to a central point, of fluid carrying energy which has been collected over a large area combine to make flat-plate thermal plants even less attractive than optical concentrating systems. A continuing improvement in the flat-plate collector for use in process-heat supply could slowly change this conclusion.

Miscellaneous Concentrators

Among the many suggestions for supply of energy at temperature levels intermediate between those required for space heating and for power production, a few examples will be presented.

Fig. 15, upper center, illustrates an intriguing way of concentrating solar energy without forming an image ([15]). All sunlight entering aperture $\overline{AB}$ at any angle lying within angle AOB will impinge on surface $\overline{CD}$, either directly or by reflection from parabolic surfaces AC and BD, whose foci are at D and C, respectively.

Let the ratio $\overline{AB}/\overline{CD}$ be designated by C(for a two-dimensional system the concentration is C, for a figure of revolution about the central axis it is C^2). It may be shown that the half-gathering angle θ is $\sin^{-1}(1/C)$

and that the system depth is the aperture $\overline{AB}$ times $\sqrt{C^2-1}(1+1/C)/2$. The disadvantage of this system over an image-forming parabola of aperture $\overline{AB}$ is its significantly greater reflecting surface. For a two-dimensional system three apertures deep, the concentration ratio is 5.1 and the half-angle θ is 11.2°.

Fig. 15, upper left, illustrates a concentrating system being tried for house heating(16). A concave-outwards spherical reflecting segment of roughly 30° included angle is used as a house roof, directly facing the sun at noon on the winter solstice. At that time an image of the sun is formed at one-half the radius of curvature of the reflector. As the sun moves away from that position the image also moves, and becomes increasingly distorted. The moving receiver must in consequence be much larger than the undistorted solar image. If the receiver is large enough and moves on the surface of an imaginary sphere the center of which is on a centrally located position about 0.22 reflector-radii out from the reflector surface and the radius of which is about 0.28 reflector-radii, the reflected radiation will be intercepted. At the winter solstice the sun moves 45° off-axis in 3 1/2 hours from noon. At the equinox at noon it is 23 1/2° off-axis and moves to 45° in 2 1/4 hours. At 45° the image is so badly distorted that the ratio of reflector aperture to receiver area is down to about 3.4; when the cosine of the angle of the sun with the normal to the reflector aperture is introduced, the number changes to 2.4. Whether the value of the concentration achieved will offset the cost of piping and controls to allow motion of the receiver has not been established.

Fig. 16 is a cross-section through a two-dimensional system of flat strip mirrors located on a circle and set to superimpose their light strips on the opposite side of the circle when the sun is in their plane of symmetry (in contrast to a curved circular mirror which would form a solar image at the half radius of the circle) (17). It is easy to demonstrate that, as the sun moves away from its central position, the locus of the point of superimposition of the strips of sunlight formed by the mirrors moves on the circle. Consequently, a receiver arranged to move on the circle will continue to intercept the light strips. There are problems of mutual shading and blocking of strips, and of significant loss of entering aperture as the sun moves from its noon position, but the device may have merit.

Non-Thermal Solar Conversion

The clever way to use the sun's energy would be to make direct use of its high energy photons. Nature does this in the photosynthesis of food and fuel in plant leaves, but man has so far had little success imitating Nature. Other approaches are feasible, however. The creation of hole-electron pairs by the absorption of light quanta of 1 to 2 electron volts and the separation of the holes and electrons at an interface between materials having a mismatch of chemical potential -- achieved at a p-n junction in photovoltaic cells and at a solid-liquid interface in photogalvanic cells -- has been used to produce an electric current. Hydrogen and oxygen have been made in minute quantities at minute energy efficiency by photoelectrolysis. These areas deserve the low-cost research support necessary to increase our understanding of the phenomena involved and, hopefully, to lead to their economic exploitation. Only one of them is far enough advanced to justify further comment here.

Photovoltaic Cells. One of the most intriguing ways to use the sun is the generation of power by photovoltaic cells, of which the silicon cell is the most promising. Developed by Bell Laboratories in the early 50's and improved continuously by research stimulated by our space program, silicon cells can deliver power at efficiencies up to 15.5% in outer space applications (the theoretical maximum is 22%) and up to 19% in terrestrial applications at air mass 2 (the higher terrestrial performance is due to the earth's atmosphere having absorbed portions of the solar spectrum not usable by the cell). Commercially available cells for terrestrial use have efficiencies of 13 to 14%. Minimization of cost was not a prime objective in the space program. Current prices for assembled arrays are of the order of \$100 per peak watt or \$1000/ft.^{2}. Cell lifetime is expected to exceed 20 years. Clearly these costs are more than two orders of magnitude greater than the capital investment for commercial power generation.

One method for reducing the high cost of cells is by concentrating the solar energy incident on them. Because cell efficiency drops with increased temperature, only moderate concentrations (up to 5) are feasible without forced cooling. The Russians, however, have used concentration exceeding 1000 with water cooling; the following of this road would introduce all the complexities and costs associated with sun-tracking (see thermal power, above).

Experts in the photovoltaic area disagree as to the prospects of cost reduction. One game that is played is to plot cost per watt on a log scale vs cumulative production on a log scale. Data extend now to 8000 square meters of total production. A straight-line extension to 20 million square meters of accumulated production brings the cost to $500/KW, estimated by the extrapolator to occur in 25 years.

Other candidate materials are available for photovoltaic cells, some better and much more expensive, some cheaper and not so good. CdS-CuS has the merit of being usable in fine-crystalline form on a film. Its efficiency is about 4%.

Many proposals for research on lowering production costs have been made, and though the view of what will happen is dim, it appears appropriate to continue supporting the effort; the end-product is so nearly ideal.

Conclusion

Solar energy is only one of many promising areas for energy research. To label a solar process prematurely as being ready to move from research to development is to increase the rate of expenditure of funds and to slight some more worthy non-solar areas. The supply of low-temperature heat is close enough to being economically sound to justify limited stimulation through incentives. The temptation to build a thermal solar power plant is high. I cannot now see that it would accomplish anything except the expenditure of funds. The future may bring a need for solar power. But if the future is to find us with the economic strength to support solar development, we must solve some of many more pressing energy problems of this decade.

Acknowledgement

The author wishes to acknowledge the debt he owes the memory of Godfrey L. Cabot, whose Solar Fund at M.I.T. supplied partial support through many years of research on how more effectively to use the sun's energy. That Dr. Cabot had vision and no illusions about the difficulty of the problem is measured by the conditions of his grant of 1938 covering a fifty year research program.

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Figures

Fig. 1 View of Lavoisier's Apparatus

Fig. 2 Mouchot's Multiple Tube Sun-Heat Absorber of 1878

Fig. 3 Solar Incidence on a Horizontal Surface. Effect of Latitude and Season.

Fig. 4 Four Flat-Plate Collector Designs

Fig. 5 The Solar Absorptivity and Low-Temperature Emissivity of a Layer of Copper Oxide on Aluminum, as Affected by Layer-Thickness.

Fig. 6 Equilibrium Temperature of No-net-output Collectors

Fig. 7 Efficiency of Solar Collectors of Different Design, as Affected by Collection Temperature. (Solar incidence constant at 300 Btu/ft^{2}hr, or 0.95 KW/m^2)

Fig. 8 Collector Performance at Various Stations over the Earth - Effects of Tilt, Number of Panes, Glass Surface Treatment, Time of Year.

Fig. 9 The First M.I.T. Solar House, Cambridge, Mass., 1939.

Fig. 10 Second M.I.T. Solar House

Fig. 11 Third M.I.T. Solar House, Cambridge, 1949

Fig. 12 M.I.T. Solar House 4, Lexington, Mass., 1956

Fig. 13 Relation of Heating Load to Solar Incidence and Available Energy (for a house located in Blue Hill, Mass.)

Fig. 14 Tower Power Plant (^{12})

Fig. 15 Bottom, Special Receiver Shape for Rim Heliostats of Tower Power Plant; Top Center, Non-image-forming Concentrator; Top Left, Stationary Roof and Moving Receiver, Proposed for House-heating

Fig. 16 Non-moving Flat-stripmirror Collector, Superimposing Images at a Locus Moving on a Circle.

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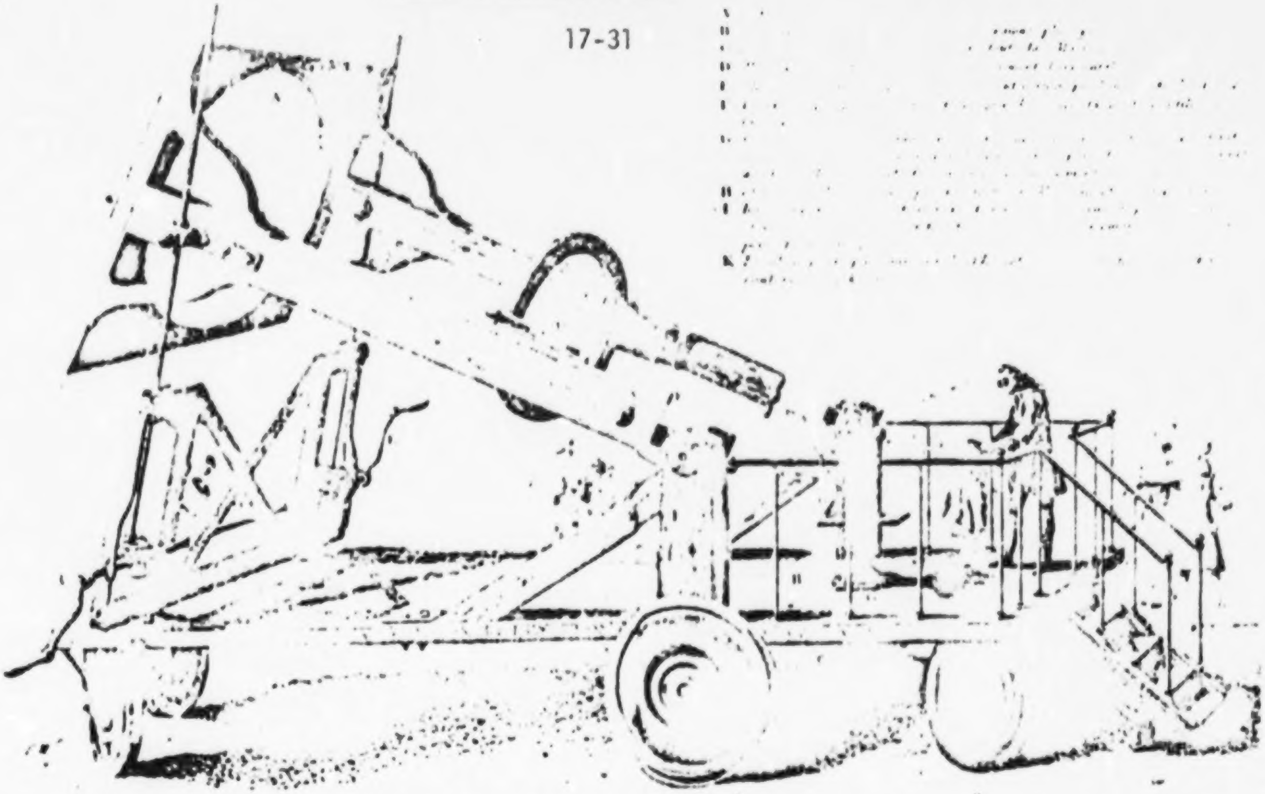

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Figure 1. View of Lavoisier's apparatus

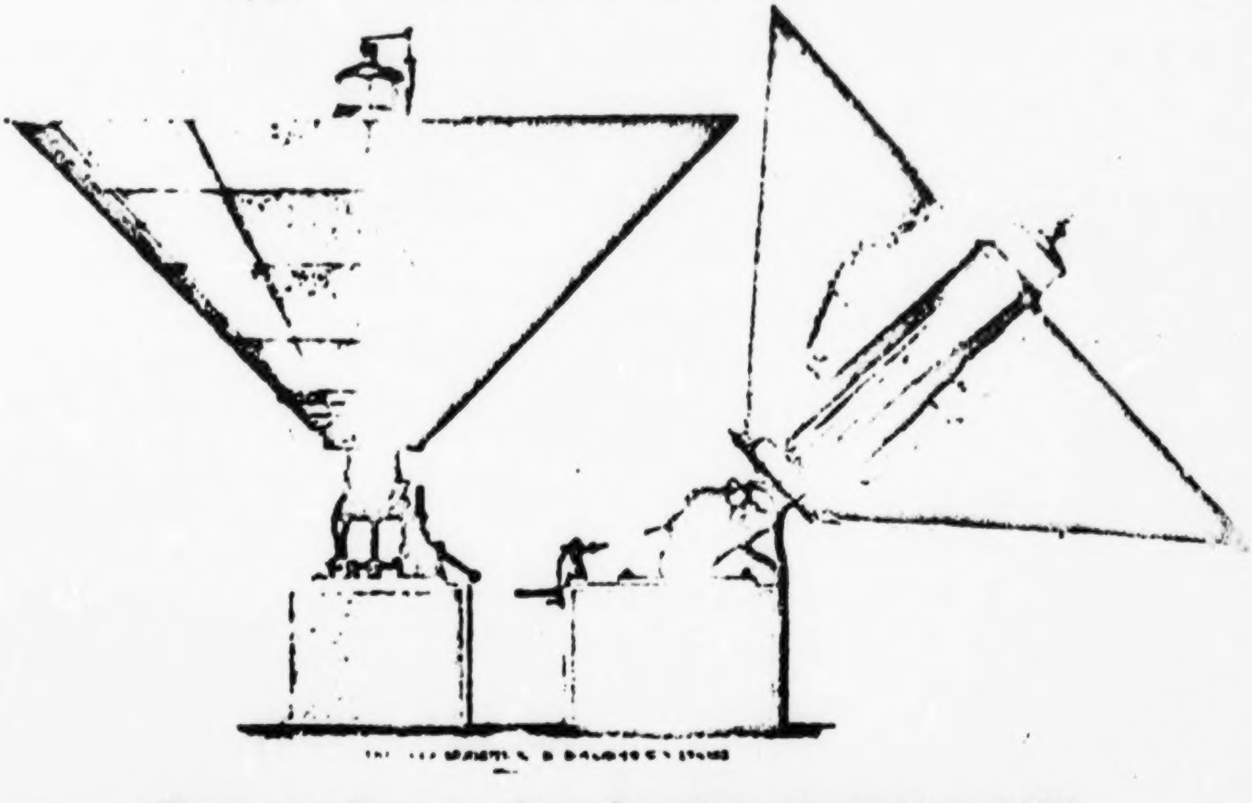


FIGURE 2 MOUCHOT'S MULTIPLE TUBE SUN-HEAT ABSORBER OF 1878.

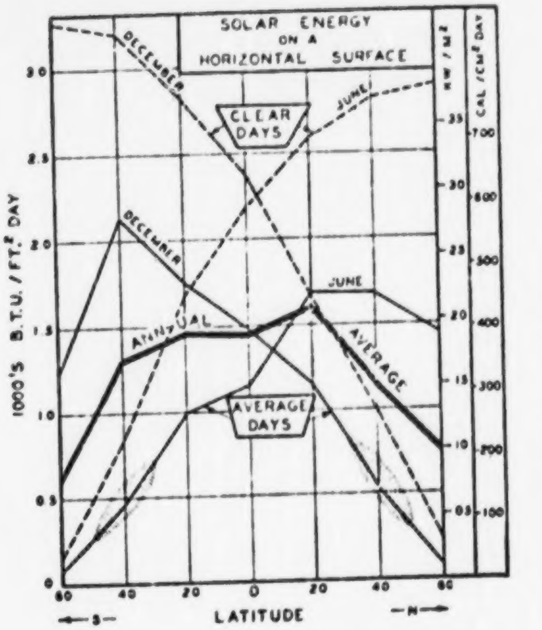


Fig. 3. Solar incidence on horizontal surfaces, average effect of latitude and season.

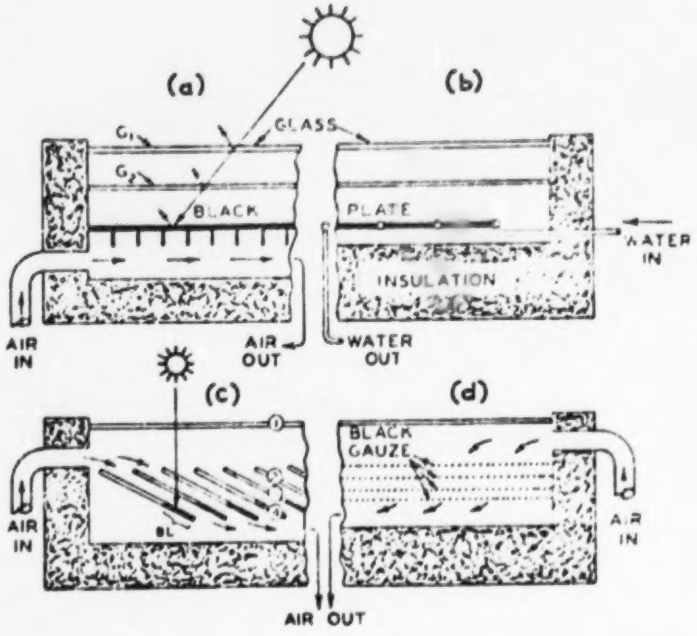

(a)
(b)
(c)
(d)
GLASS
G_1
G_2
BLACK
PLATE
WATER IN
INSULATION
AIR IN
AIR OUT
WATER OUT
BL
BLACK GAUZE
AIR IN
AIR IN
AIR OUT

Fig. 4. Four types of flat-plate collectors.

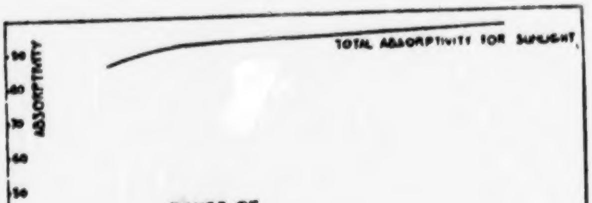
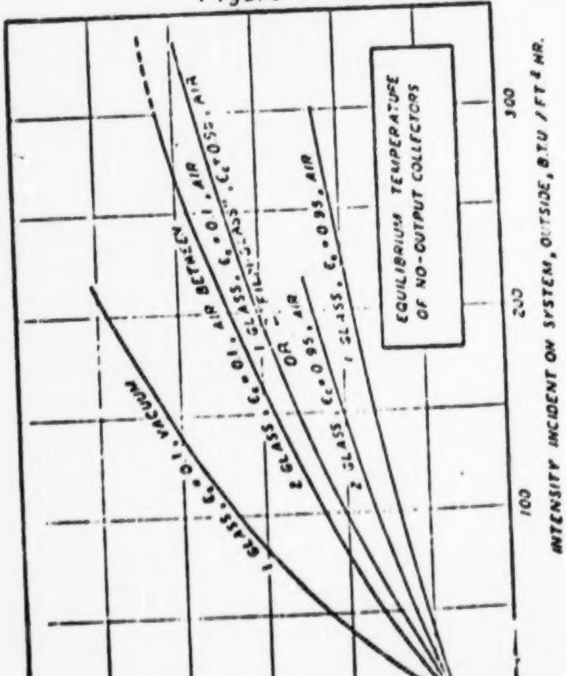


Fig. 5—The absorptivity and emissivity of samples prepared under optimum conditions, as affected by deposit thickness.

Figure 6



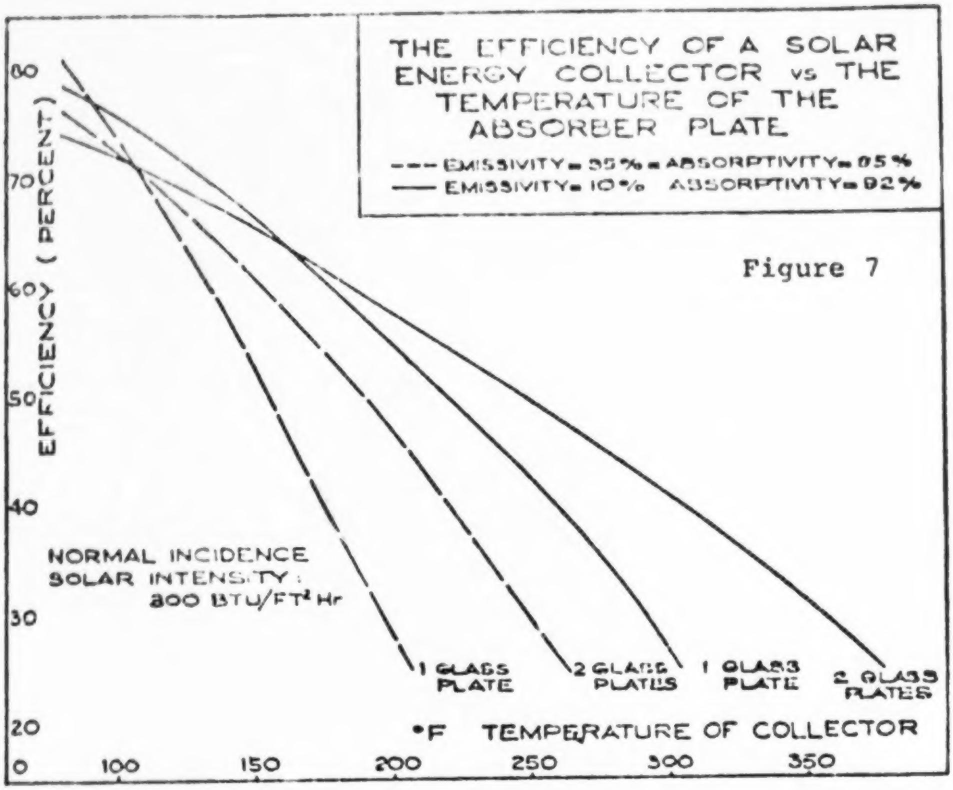


Figure 7

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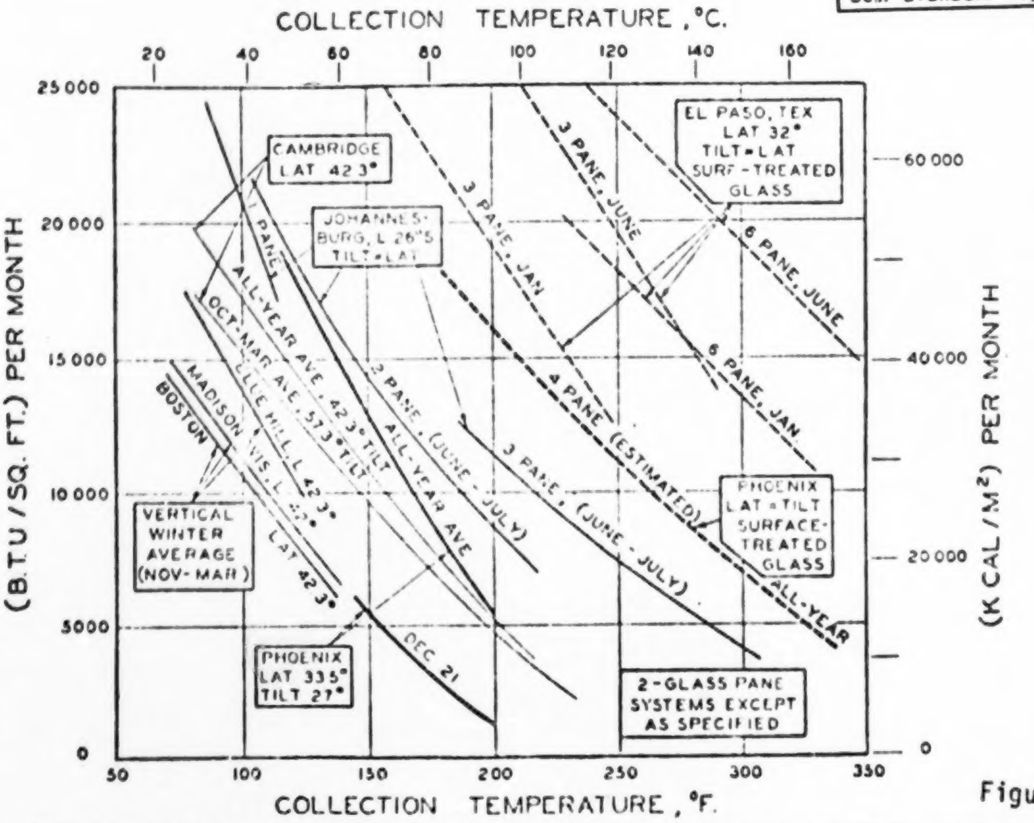

Figure 8

Fig 8. Collector performance at various stations over the earth — effects of tilt, number of panes, glass surface treatment.

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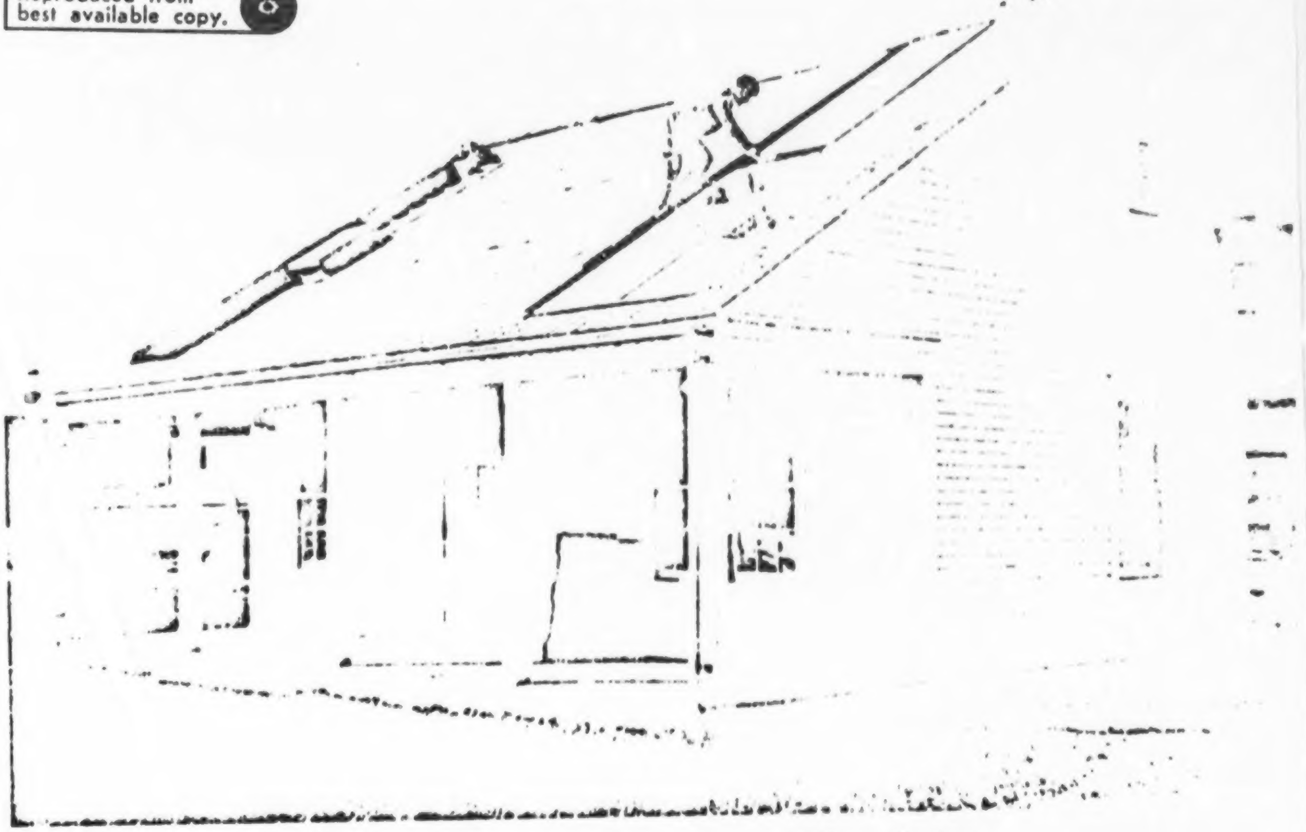

Figure 9. First M. I. T. Solar House

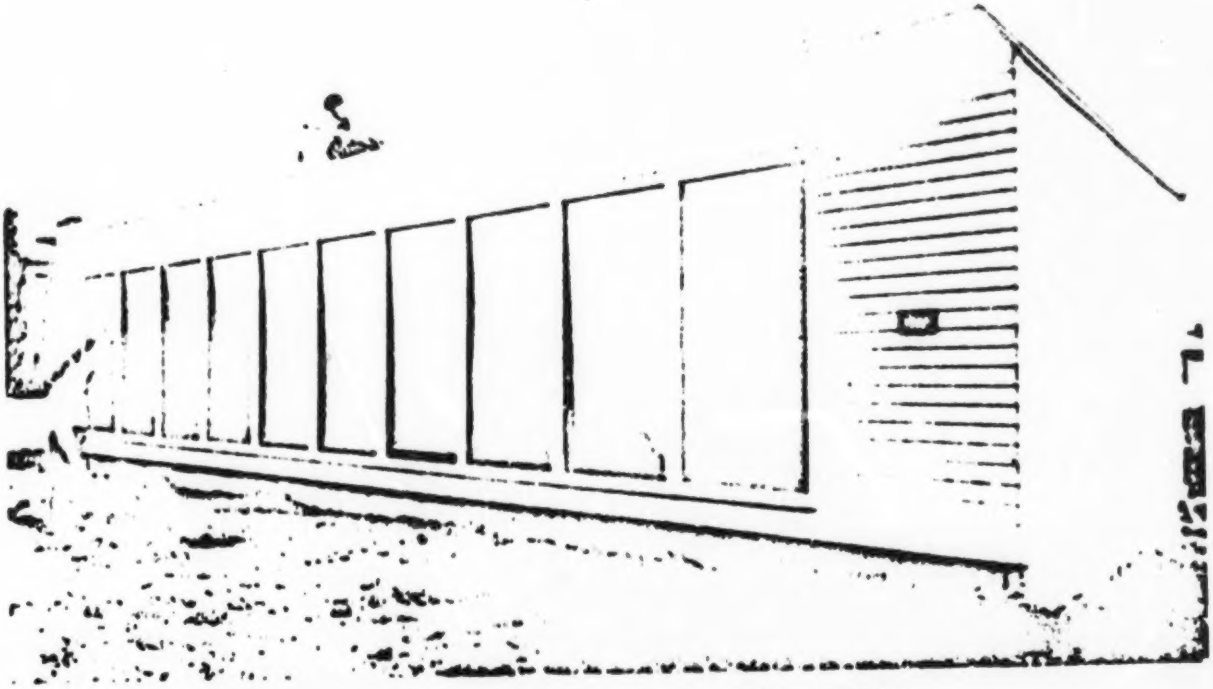

Figure 10. Second M. I. T. Solar House

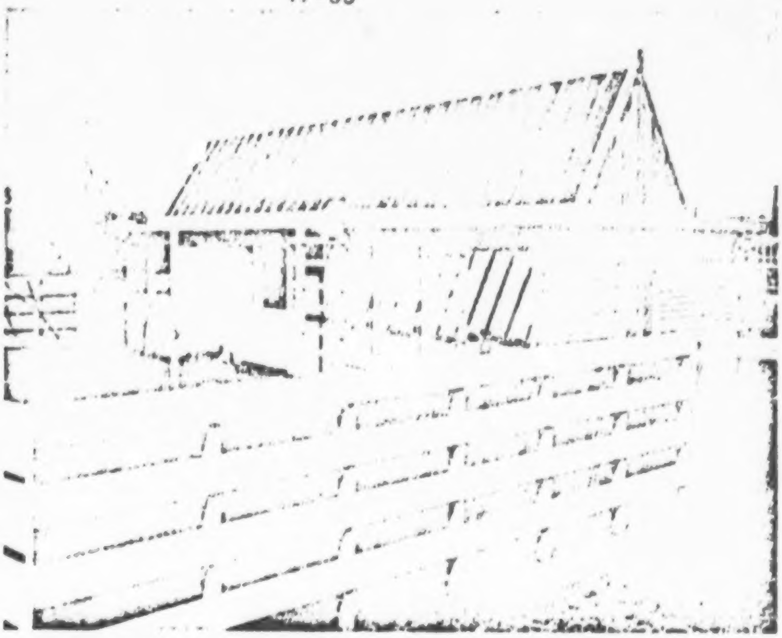

Figure 11. Third M.I.T. Solar House

Figure 12. Fourth M. I. T. Solar House

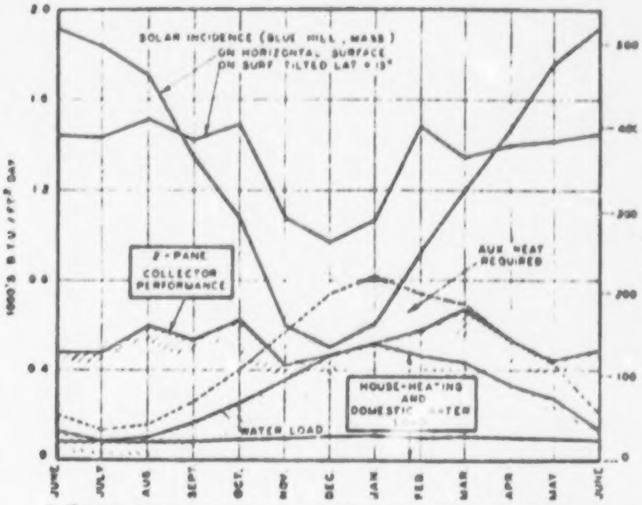

Fig. 13. Relation of heating load to solar incidence and available energy (for a house located in Blue Hill, Mass.)

Figure 13

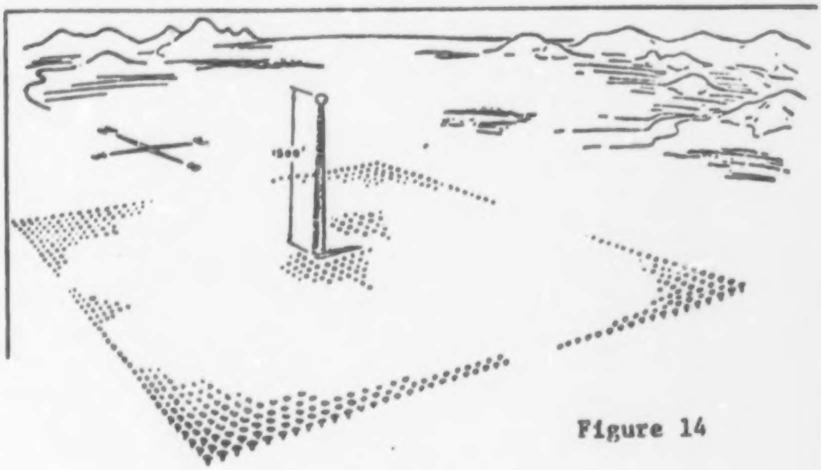

Figure 14

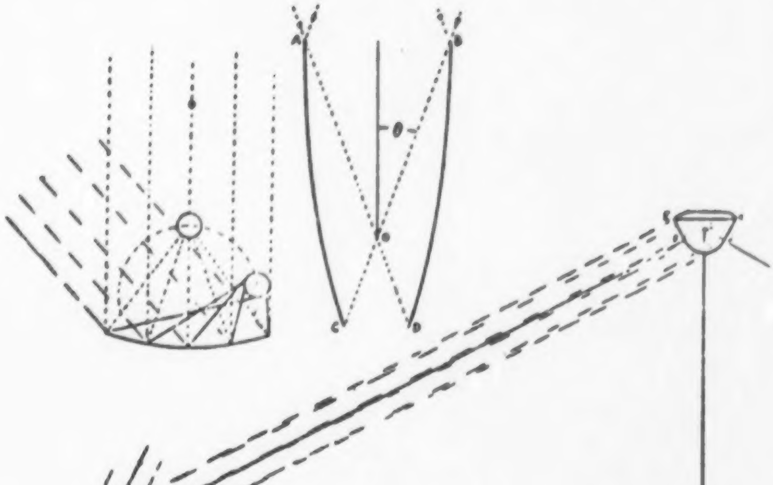

Figure 15

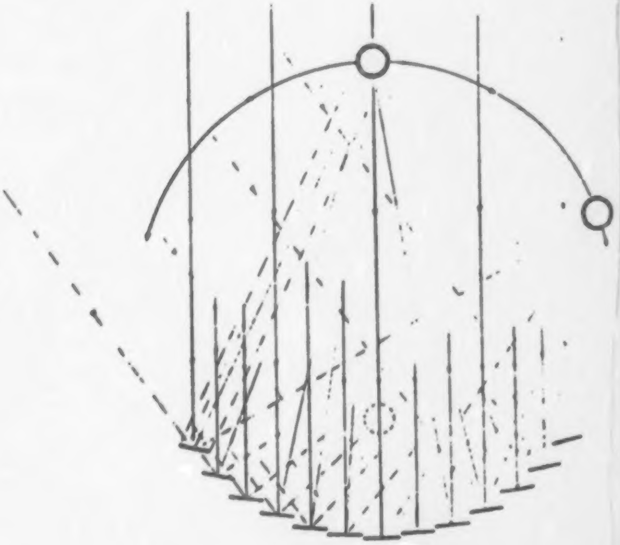

Figure 16